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ENVIRONMENTAL CONTAMINANTS PROGRAM
ON-REFUGE INVESTIGATIONS SUB-ACTIVITY

AZ - Backwater Manipulations for Endangered Fishes: Management Implications of Selenium on National Wildlife Refuges of the Lower Colorado River

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Final Report

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ABSTRACT

Many studies have evaluated selenium in the lower Colorado River, but none have reviewed selenium levels after river water has been directed into previously isolated backwaters. Radtke et al. (1988) hypothesized that the source of selenium was the upper Colorado River Basin and that backwater lakes along the river were sinks for selenium contamination. Subsequent research has reported that backwater lakes could become selenium sinks when lower Colorado River water is introduced into isolated backwater lakes originally fed by groundwater and where low exchange rates increase retention time. Backwaters created as isolated native fish habitats in partial fulfillment of the Reasonable and Prudent Alternatives of the Service's Biological Opinion on the Bureau of Reclamation's operation of the lower Colorado River allow the fish to grow in a predator-free environment, but also may be contributing to selenium bioaccumulation along the lower Colorado River.

Our goals in this study were to conduct a pre- and post-backwater manipulation investigation of created backwaters. To assess selenium accumulation in backwaters, we sampled water, sediment, and macroinvertebrates in 2001 and 2004. We also collected fish tissues in 2001-2004 for a baseline analysis on native fish stock in constructed, isolated backwaters.

We compared Beal Lake (Havasu National Wildlife Refuge (NWR), Arizona (AZ)) and the DU Ponds (Imperial NWR, AZ), newly constructed/engineered experimental backwaters, with Office Cove (Bill Williams River NWR, AZ) and High Levee Pond (Cibola NWR, AZ), which were previously constructed and established backwaters. Management of the experimental backwaters changed during the study, in an attempt to meet the objectives of the isolated native fish habitat project. One of the most significant changes occurred at the DU Ponds when pumped groundwater replaced the mainstem river water supply as a measure to reduce non-native fish infiltration. The use of only groundwater at the DU Ponds may have affected selenium accumulation. The other changes led to our inability to detect patterns between years, especially in fish tissues.

We detected some significant differences between selenium concentrations over time. Selenium concentrations in water increased significantly during the four year study at Office Cove (Table 1). Most sediment samples had greater selenium concentrations in 2004 although the only significant difference was at Beal Lake. Crayfish selenium concentrations were higher at Beal Lake and the DU Ponds than in Office Cove and High Levee Pond in 2001, but very little selenium was detected in 2004 invertebrate composite samples.

Selenium concentrations in crayfish were slightly lower than those previously reported in other backwater studies. Concern for the potential for selenium bioaccumulation in lower Colorado River backwaters still exists. Other metals of potential concern that we found include zinc and copper.

Table 1. Summary of selenium concentrations in all matrices sampled. Most comparisons are between 2001 and 2004, but fish tissues were collected in 2002 and 2004 as well.

Selenium only (ppm)	Beal Lake -01	Beal Lake -04	Office Cove-01	Office Cove-04	High Levee Pond-01	High Levee Pond-04	DU-01	DU-04
Water ww[1] (n=6)	0.0006	0.0006	0.0003	0.0006	<0.0003	<0.0004	0.0006	0.0003
Sediment dw (n=6)	1.6	3.2	1.0	<1 to 17	1.0	1.7	<0.5	1.0
Crayfish dw (n=1-6) (start at <0.4)	1.3 after 1 month		0.6 after 1 month		0.6 after 1 month		1.4 after 1 month	
Other fish dw				(2.7 in bonytail from Lake Havasu)	(6.1 in mosquito-fish at West Meander)			
Razorback Suckers dw (n=10-12)	(2002 hatchery stock = 1.2)							(2004 hatchery stock = 2.4)

[1] ww = wet weight and dw = dry weight.

We did document continued selenium bioaccumulation in crayfish and fishes, but water concentrations of selenium seem diminished in comparison to previous field studies.

Creation of lower Colorado River backwaters should be monitored for selenium concentrations pre- and post-manipulation, especially post-manipulation. We propose using High Levee Pond as a reference site in all future backwater studies along the lower Colorado River because it consistently had low concentrations of selenium in water, sediment, and crayfish and it had water quality measurements suggesting it was a connected backwater. Connected backwaters are most similar to the mainstem of the river because of their higher flushing rates and lower water residence times. We believe that continued monitoring is warranted at Beal Lake since it consistently had high concentrations of selenium in water, sediment, and crayfish. We also suggest selenium monitoring at Willow Beach since it is a significant hatchery for native fishes in the southwest.

INTRODUCTION

Background and Justification

The Service issued a Biological Opinion (FWS 1997) on the Bureau of Reclamation's (BOR) Description and Assessment of Operations, Maintenance, and Sensitive Species of the Lower Colorado River. In the Reasonable and Prudent Alternatives (RPA) of the Opinion, the Service's provisions required BOR to construct isolated native fish habitats for augmentation of the federally endangered razorback sucker (*Xyrauchen texanus*) and endangered bonytail (*Gila elegans*) populations. Backwaters of the lower Colorado River National Wildlife Refuges were prepared as isolated native fish habitats for future stocking of razorbacks and bonytail in partial fulfillment of the RPA. Isolation allows passage of water and nutrients while excluding the passage of recreational and sportfishing craft, the ingress of undesirable fishes, and egress of protected fishes. In the past, isolated backwaters were successful in providing *in situ* growout facilities for these fishes, free of the pressures of predation and competition from nonnative fishes (USFWS 2004). However, such backwaters may be susceptible to accumulation and bioaccumulation of selenium depending on site selection, design, and implementation. Selenium in the mainstem lower Colorado River currently averages, and at times exceeds, 2 ppb (USGS 1996, 1997, 1998). When selenium in water exceeds 2 ppb, there is increased potential for foodchain bioaccumulation and subsequent reproductive impairments in fish and aquatic birds (Lemly 1996).

Selenium is a semi-metallic element associated with Cretaceous shales abundant in the upper Colorado River Basin. Selenium is released from parent rock and soil through weathering, oxidation, and anthropogenic activities such as mining and agricultural irrigation, and is mobilized throughout the lower Colorado River Basin (Lemly 1996; Presser 1994; Presser et al. 1994; Welsh and Maughan 1994; Radtke et al. 1988). Although trace amounts of selenium are considered an essential dietary element for most organisms, at higher concentrations it can be more toxic than arsenic or mercury (Sorensen 1991). The chemical properties of selenium resemble sulfur, and uptake occurs readily in protein synthesis; if allowed to cycle within the food chain, selenium tends to bioaccumulate and can adversely affect higher order sensitive wildlife (Ohlendorf 2003, Martinez 1994, Rusk 1991, Sorensen 1991).

Studies in the upper Colorado River Basin have documented selenium-induced reproductive impairments in razorback sucker and bonytail (Hamilton 1994, Buhl and Hamilton 1995, Waddell and May 1995). Selenium is implicated with toxic effects to other aquatic organisms and biota (such as fish-eating birds) utilizing aquatic organisms as prey, and has been linked to deformities, reproductive impairments, and mortality (Ohlendorf 2003). Studies in the lower Colorado River Basin have documented potentially toxic levels of selenium in fish-eating birds (Radtke et al. 1988; Rusk 1991; Martinez 1994; Andrews et al. 1997).

Colorado River backwaters were previously categorized as two types: seepage lakes and connected lakes (Holden et al. 1986). Seepage lakes are unconnected, isolated backwaters without a direct physical connection to the river that are fed by high groundwater and seepage through the soil from the river. Connected lakes are those with a direct physical connection to the river. Seepage lakes tend to be warmer and shallower than connected lakes, and water quality parameters are significantly higher in conductivity and salinity (but with little to no selenium compared to connected lakes). Prieto (1998) added a third backwater category that we also used in our study. He defined "pseudo-seeps" as backwaters with no distinct connection to the mainstem river, but in fact were inconspicuously connected with flow exchanged through coarse substrates, vegetation thickets, and beaver/muskrat tunnels. Prieto reported that most pseudo-seep water quality parameters resembled connected backwaters, influencing him to redefine backwaters based on the degree of connectivity to the mainstem channel, productivity, water quality, and selenium dynamics. Selenium concentrations in pseudo-seeps are similar to those in connected lakes, although usually not quite as high. Pseudo-seep lakes have higher productivity when compared with the other two backwater types; wildlife and plants appear to be more diverse in pseudo-seeps (Prieto, pers. comm.). Prieto (1998) also suggested that converting seepage lakes to pseudo-seeps may improve some water quality parameters, which in turn would improve the fisheries value. However, a "selenium sink" situation may be established in constructing isolated native fish habitats by converting seepage lakes into pseudo-seeps (by increasing water exchange with the mainstem Colorado River), or by reducing flow exchange in connected lakes.

Lusk (1993) and Prieto (1998) cautioned that opening seepage lakes to exchange with mainstem water would increase selenium exposure and accumulation. Several studies have suggested that water quality can be predicted by the degree of connectivity of backwaters to the mainstem Colorado River (Prieto 1998; Lusk 1993; Holden et al. 1986; Saiki 1976; Kennedy 1979). The degree of connectivity is defined as the rate of flow exchange with the mainstem Colorado River, which is a function of distance from the mainstem river and of substrate porosity. No studies have been conducted in the lower Colorado River Basin to investigate selenium accumulation in a previously selenium-low environment. If management actions continue without consideration of scientific cautions (Lusk 1993, Prieto 1998), there may be a loss of available habitat areas that are selenium-low through increases in selenium exposure via Colorado River water. We hypothesized that with appropriate knowledge and implementation, filter-barriers and flow-through design can function to reduce selenium-loading. The focus of this study was to monitor selenium concentrations in fish and wildlife among differentially connected backwaters and to offer the assessments derived from this study for future management consideration.

Scientific Objectives

1. Conduct initial, early post-manipulation surveys and sampling of subject backwaters.
2. Assess trace elements in water, sediment, and macroinvertebrates. Assess baseline tissue burdens in pre-stocked native fishes.
3. Conduct secondary post-manipulation surveys and sampling of converted backwaters.
4. Assess trace element concentrations in water, sediment, macro-invertebrates, and stocked fishes over time.

METHODS

Data Collection and Analysis

Study areas: Beal Lake (Havasu NWR), Office Cove (Bill Williams River NWR), High Levee Pond (Cibola NWR), and Ducks Unlimited Ponds (DU Ponds, Imperial NWR) (Figures 1-4) served as our primary study areas. Beal Lake and the DU Ponds were our experimental or treatment sites and Office Cove and High Levee Pond were our reference sites. Prior to our study, none of these sites had been defined as a connected lake, pseudo-seep, or true seep. None were likely to be a true seep, however, because all were connected to the river in some way.

Post- manipulation of these sites refers to manner in which the backwaters where connected to the mainstem of the river; renovated and kept free from invasive non-native fish species; and native fishes added and successfully maintained. The description and status of the backwaters are as follows:

Experimental Treatment Locations:

Beal Lake

Beal Lake is a pseudo-seep and is 200 acres at full pool. This backwater receives water via a gravity-fed inlet channel from Topock Marsh which in turn receives water from the lower Colorado River and has an outlet culvert that flows from Beal Lake back to the river (Figure 1). Both the inlet channel and the outlet culvert had semipermeable berms installed prior to this study to stop the infiltration of non-native fishes because Beal Lake existed without berms before our study began. Topock Marsh also functions as a backwater lake in that it is off the mainstem channel, but river water flows into the marsh through a long inlet canal at the north end of the marsh and back out of the marsh through another long outlet canal back to the mainstem of the river. Beal Lake dredging and semipermeable berm construction was completed prior to May 2001; piscicide applications removed nonnative fishes prior to stocking with native endangered fishes.

Construction of this isolated native fish habitat was complete in 2002. Razorback suckers were stocked in 2002, but none were found a month after stocking (Chuck Minckley, pers. comm.). Biologists suspect that fish-eating birds ate most of the fish. Subsequently, non-native fish were found in Beal Lake. Renovation occurred in early 2004. Since the last samples were collected in July 2004, new impermeable berms with barrier screens were installed in the inlet and outlet canals to keep eggs and fishes out of Beal Lake. Now that the new, impermeable structures are in place, managers plan on renovating Beal Lake again in the summer of 2005 with extremely low water levels to ensure effective piscicide treatment (Chuck Minckley, pers. comm.).

DU Ponds

The DU complex is comprised of four ponds connected in a series from north to south (Figure 2). The DU Ponds are on the western edge of the farm field units. The Colorado River lies directly to the west of the DU Ponds/farm fields, separated from the ponds by an earthen road. Martinez Lake is southeast of the DU Ponds. The surface area of all of the ponds does not exceed 45 acres. The northernmost pond, Pond 1, is the smallest pond. Pond 2 is directly south of Pond 1 and is the shape of a dumbbell. Due to the shape of Pond 2, the long middle stretch of the pond often has low dissolved oxygen (DO) concentrations. A wind-driven aerator was added to this pond to eliminate this problem, but it has not been correcting the low oxygen problem (Chuck Minckley, pers. comm.). Pond 3 is immediately to the south of Pond 2 and is the shape of the letter L. Pond 4 is the last pond and is furthest south of all the ponds. Each pond has its own inlet structure from the pond before it, so the ponds can be isolated and managed individually, when necessary. Water flows out of Pond 4 back into the lower Colorado River through a culvert.

While water levels in these ponds have been managed, high water temperatures and non-native fish infiltration have caused delays in project progress. The DU Ponds required piscicide application prior to stocking with native endangered fishes. Lower Colorado River water was being used to fill the ponds, but managers suspected that non-native fish eggs were still making their way into the system. Therefore, pond management switched from river water to groundwater, which then changed this site for the purpose of this study (Chuck Minckley, pers. comm.). Then, Pond 1 was renovated and restocked in 2004; temperature and DO requirements were maintained by pumping groundwater from midnight to dawn. Managers were successful in maintaining 4,500 razorback suckers in Pond 1 in 2004. The plan is to continue managing this pond the same way in 2005. However, Ponds 2-4 are going to be destroyed and completely re-designed in 2005-2006. We classified them as a pseudo-seep until the change in water management in 2004. Their current classification is unknown.

Reference Locations:

<u>Office Cove</u>

Office Cove is a 2.5 acre diked cove off of Lake Havasu on the Bill Williams River NWR. It is a pseudo-seep. It was created before we began our study. Samples collected at Office Cove serve as a reference, but no real pre- and post-manipulation data were gathered here.

Office Cove receives lower Colorado River water from Lake Havasu through a semipermeable berm on its northwestern edge (Figure 3). The other three sides of the backwater topographically exclude lake access. It had a wind-blown aeration unit placed in the middle of the pond. The water elevation in Office Cove is at equilibrium with the elevation of the water outside of the cove. Water exchange occurs through the berm in either direction (Office Cove → river or river → Office Cove) until hydraulic equilibrium occurs. Due to its size it has also experienced high water temperatures and low DO concentrations. A solar-powered aerator has since been added. Office Cove is not actively managed right now. Native fish have not been held in this pond since 2002.

Figure 3 also shows where the confluence of the Bill Williams River is with Lake Havasu (green portion of map). All crayfish (*Procambarus clarkii*) were collected from the Bill Williams River and then placed into separate backwaters for *in situ* exposures (See Methods: Invertebrates).

High Levee Pond

High Levee Pond is a 5-acre pond on the old lower Colorado River channel at Cibola NWR (Figure 4). High Levee Pond was formed at the top of the old river channel when a semipermeable berm was installed in the old river channel in the late 1960s. We classified High Levee Pond as a connected backwater. Native fishes were stocked in High Levee Pond in 1993-1996 (Lesley Fitzpatrick, pers. comm.). Water infiltrates into the top of the old river channel and flows through High Levee Pond as it did before it was diked off from the rest of the old river channel. Water exchange in High Levee Pond occurs by gravity and the natural flow of the river. The Palo Verde Irrigation Drain enters the old Colorado River channel below High Levee Pond, so it does not influence water quality in High Levee.

This isolated native fish habitat is the only successful backwater to date. Razorback suckers and bonytail are intensively monitored here. This backwater was created decades before we began our study; therefore, samples collected at High Levee Pond serve as a comparison between years and as a reference. Biologists have recently concluded that non-native fish infiltration has occurred above levels suitable for an isolated native fish habitat since our study was completed. Biologists anticipated management of the isolated backwaters such as this would be required and plan to renovate this backwater in late 2005. All razorback suckers and bonytails will be transferred to the mainstem of the lower Colorado River, to Beal Lake, or to the DU Ponds.

Figure 1. Beal Lake at Havasu NWR, Arizona was a treatment sampling site in this study.

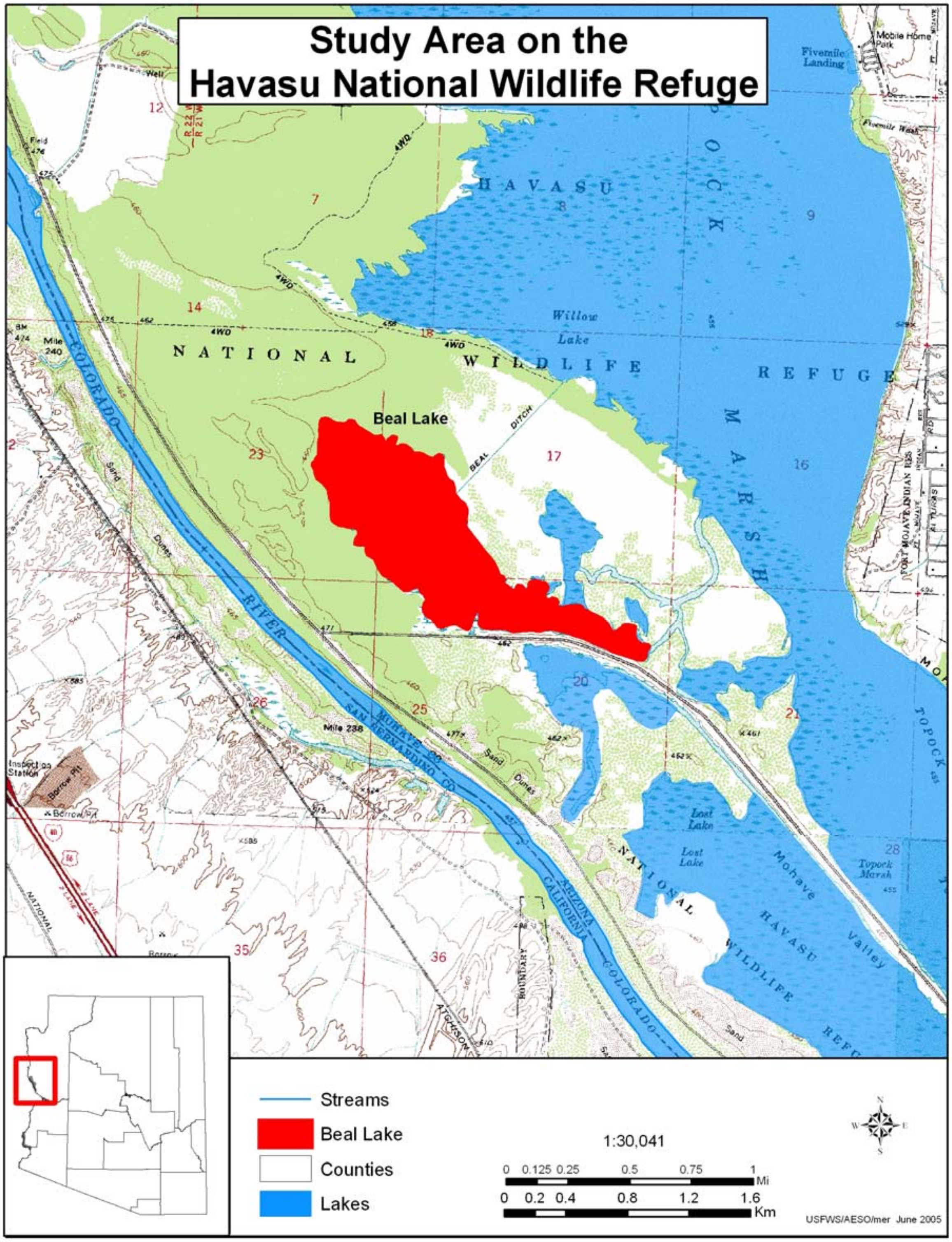


Figure 2. The DU Ponds at Imperial NWR, Arizona were treatment sampling sites in this study.

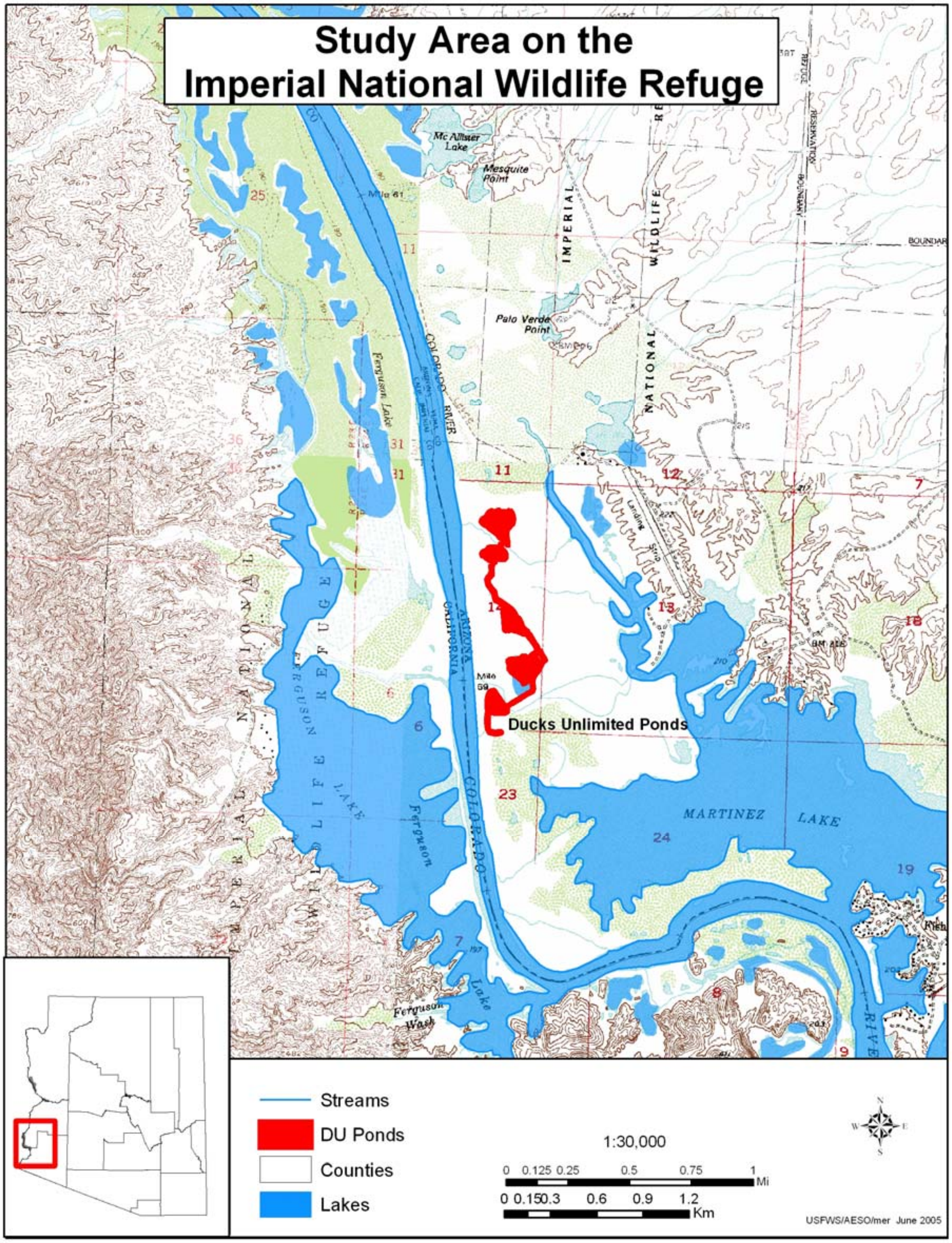


Figure 3. Office Cove at Bill Williams River NWR, Arizona was a reference site in this study.

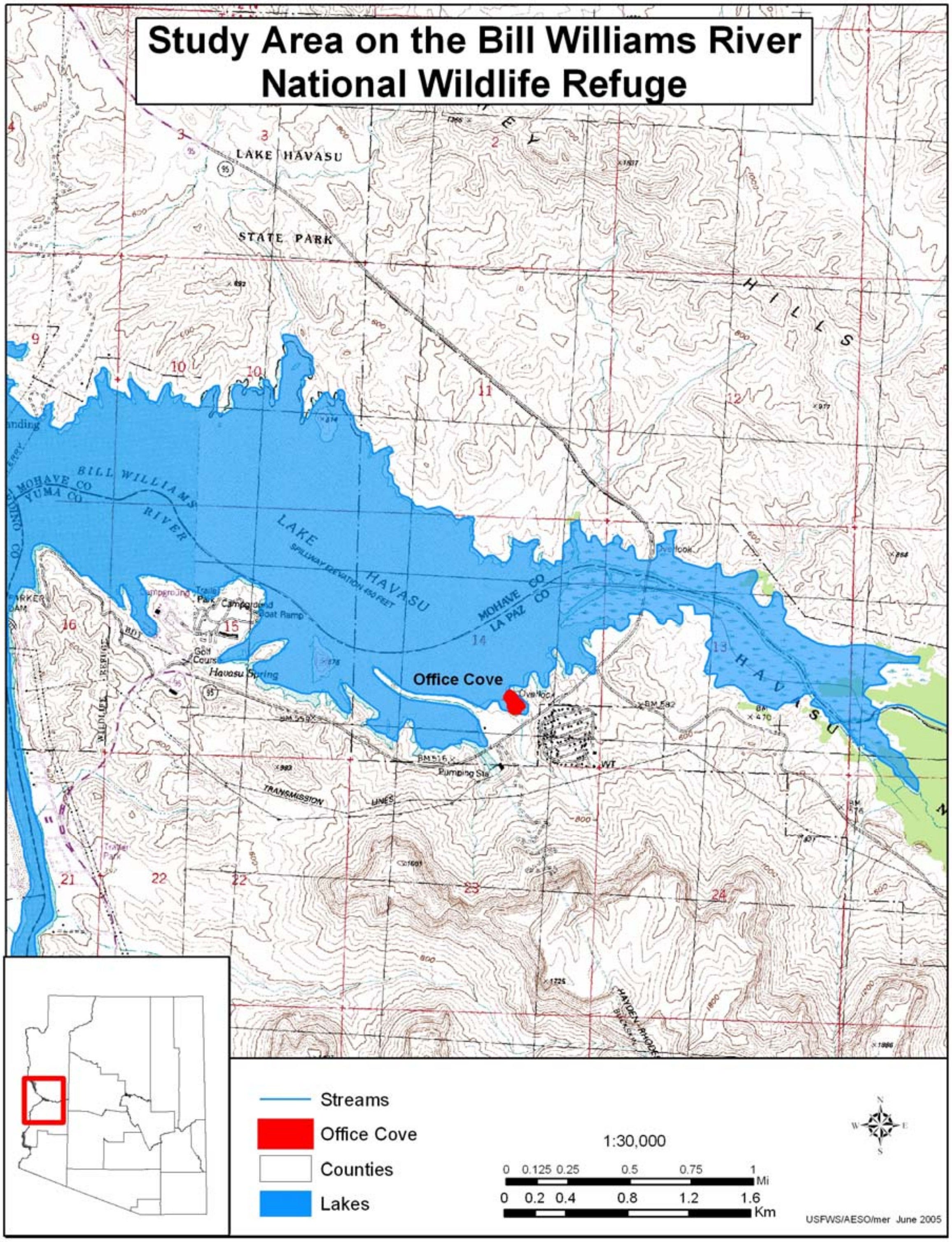
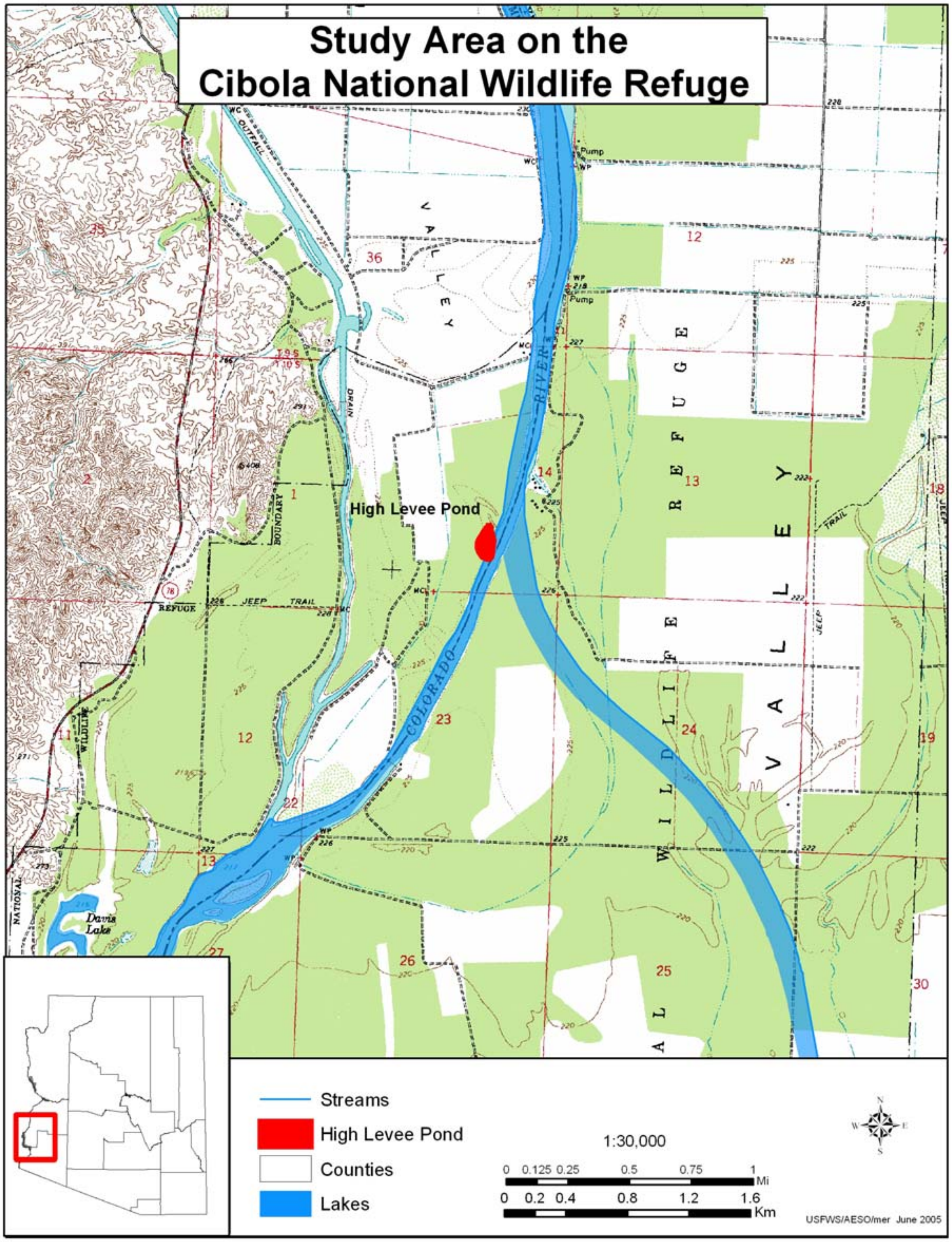


Figure 4. High Levee Pond at Cibola NWR, Arizona was a reference site in this study.



Surveys: Mitch Thorson of Parker Fisheries Resource Office and Refuge personnel assisted in collecting water quality measurements. Water quality was also collected by Gordon Mueller and Arizona Ecological Services Field Office (AESO) personnel at High Levee Pond. We collected quarterly water quality data in 2004 (Appendix 1). If cooperators were sampling, they sampled at the deepest portion of the water body and took water quality measurements at 0.5 m intervals from the surface to the zone immediately above the backwater bottom. When AESO took measurements, we collected data at every water and sediment collection site (n=6 per backwater) at 0.5 m intervals from the surface to the zone immediately above the bottom. We did not map post-manipulation backwaters for surface area and depth to estimate volume. Pre- and post-manipulation flow exchange and thickness of filter-barriers as a measure the degree of the backwaters' connectivity also were not measured. We attempted to measure backwater flow exchange and retention at inlet and outlet structures using a flowmeter, but were unsuccessful because water flow was at steady state in some of the backwater dams and inlets or was not otherwise measurable with the techniques we used. Water exchange occurred too slowly to be measured with a regular staff flow meter for streams; therefore, backwater flushing rates were not quantified.

Sample collections: Samples of water, sediment, and macroinvertebrates were collected at each backwater; samples were collected at designated sites in the early and late post-manipulation phases of this project. Designated sites were selected to represent available habitats/conditions, and included the proposed filter-barrier inlet and outlet sites. In anticipation of lost or vandalized site markers the designated sites were recorded using a GPS unit. All Beal Lake and the DU Ponds were sampled before stocking in August and September 2001 and in the late post-manipulation phase in July 2004. Field collections were also made during the same months in 2001 and 2004 at the Office Cove and High Levee Pond - the two reference locations that held razorback suckers and bonytails. Native fish in Office Cove have since either died-out due to low dissolved oxygen or were transferred to other holding facilities (Chuck Minckley, pers. comm.).

Water: Specific conductance, pH, DO, and temperature were measured quarterly (1 day) in each backwater only in 2004 by Refuge and fisheries personnel. Six, 1-liter unfiltered water samples were collected in 2001 and 2004, in the vicinity of the designated site markers, at each backwater for metals-scan in the early and late post-manipulation phases of this project. Samples were collected in chemically-cleaned jars, metals-scan samples were preserved with HNO_3 to pH<2, and all water samples were transported and stored at 4°C (Csuros 1994).

Sediment: Six sediment samples were collected at each backwater in the early and late post-manipulation phases of this project (2001 and 2004). Surface samples were collected by Eckman dredge (USFWS 1986) in the upper 2 to 4 in of sediment of the backwater. Each sample was a homogenized composite of 5-6 individual sub-samples collected in the vicinity of the designated site markers. Each sample was collected at the same site where water was collected. Sub-samples were thoroughly mixed in a stainless steel container and saved in a pre-cleaned glass or plastic jar. Samples were kept at 4°C until shipment to the laboratory for future analysis. We did not analyze grain size.

Invertebrates: One composite sample of aquatic macroinvertebrates common to all sites (e.g., dragonfly nymphs (Odonata), freshwater clams (*Corbicula*), etc.) was targeted for collection by aquatic invertebrate bag-traps prepared for colonization. We tried to collect a minimum of 10 g composite of mixed taxa from each backwater in the vicinity of the designated site markers during the early and late post-manipulation phases of this project. Aquatic macroinvertebrate samples were too small by site, and samples were composited for each location to reach a minimum acceptable weight for chemical analyses. We set out bag-traps one month prior to collection. They were collected September 11-13, 2001 and August 16-17, 2004. Macroinvertebrates were counted, weighed, placed in air-tight plastic bags, and stored frozen for future analyses (USFWS 1986).

Anticipating low yields in the aquatic macroinvertebrate bag-traps, *in situ* crayfish cages were placed adjacent to bag-traps in 2001. Crayfish used for the *in situ* treatment were collected from the Bill Williams River NWR, and were allowed to depurate for two weeks with no food in dechlorinated municipal tap water in the AESO laboratory before placement at each location. Eight to ten crayfish were placed in each cage for approximately one month before harvest. Six cages were placed on the bottom of the backwater to increase exposure to the bottom substrate and to allow the crayfish access to food; invertebrate bag-traps and crayfish cages were placed mid-August and harvested mid-September 2001. Crayfish were counted, composited, and placed in air-tight plastic bags, and stored frozen for future analyses (FWS 1984). So as not to assume that depuration was 100% effective, pre-depuration and depurated crayfish samples were also submitted for analyses to determine the effects of depuration vs. "baseline" tissue concentrations in crayfish obtained from the Bill Williams River.

Fishes: Samples of pre-release, whole-body razorback suckers were taken from Beal Lake in 2002 and the DU Ponds in 2004 to document early post-manipulation selenium concentrations. Razorback suckers in 2002 ranged from 118-198 mm total length and 15-75 g. Razorback suckers in 2004 ranged from 82-126 mm total length and 4.5-17.7 g. We also collected a composite sample of mosquitofish (*Gambusia affinis*) from West Meander at Cibola NWR in 2001 (length unknown; 41.0 g total for composite). We also received two bonytail trammel net mortalities from Lake Havasu in 2004 (285-310 mm total length; 122-180 g). When possible, we collected specimens in the same year/size class. Specimens were weighed and measured, wrapped in aluminum foil and frozen for future analyses (USFWS 1986).

We also used non-lethal muscle plugs to sample the DU Ponds population in 2003 before pond renovation. A 5 mm biopsy punch was used to collect the tissue samples. Fishes were measured (384-426 mm total length; 660-924 g), sampled from beneath the left side of the dorsal fin, treated with antibacterial ointment, and released using techniques developed by Waddell and May (1995) and Smith (1998). The sample sizes for the muscle plugs were less than 5 mm and we did not specify that we only wanted selenium analysis for the muscle plugs. Since we did not make this request, low sample mass resulted in higher analytical detection limits (instead of 0.5 ppm, detection limits were 2-8 ppm) and no selenium was detected in the muscle plugs.

Chemical Analyses: All water, sediment, macroinvertebrate, and fish samples were collected and preserved using methods described in the U.S. Fish and Wildlife Service (FWS) Field Operational Manual for the Resource Contaminant Assessment (Staley and Rope 1993, FWS 1996). Laboratory quality assurance and quality control was under general supervision of the FWS Patuxent Analytical Control Facility (PACF), a Field Station of the Division of Environmental Quality located at the Patuxent Wildlife Research Center in Laurel, Maryland. The PACF selected Laboratory and Environmental Testing, Columbia, Missouri for analyses, handled the procurement, and authorized the FWS client to ship the samples. The following elements are included in standard testing by PACF and were quantified for all water (ppm, wet weight), sediment, macroinvertebrates, and fish tissue (ppm, dry weight) samples:

Al (Aluminum), As (Arsenic), Ba (Barium), Be (Beryllium), B (Boron), Cd (Cadmium), Cr (Chromium), Cu (Copper), Fe (Iron), Pb (Lead), Hg (Mercury), Mg (Magnesium), Mn (Manganese), Mo (Molybdenum), Ni (Nickel), Se (Selenium), Sr (Strontium), V (Vanadium), and Z (Zinc).

Arsenic and selenium concentrations were determined by hydride generation atomic absorption (US EPA 1987). Mercury was quantified by cold vapor atomic absorption (US EPA 1984). Lead was analyzed in water and animal tissue using graphite furnace atomic absorption (US EPA 1987). All other elements were analyzed by inductively coupled plasma (ICP) atomic emission spectroscopy (Dahlquist and Knoll 1978, US EPA 1987) or ICP. The laboratories maintained quality assurance and quality control (QA/QC) by analyzing blanks, duplicates, and spiked samples. The PACF monitored QA/QC. Analytical methodology and reports met or exceeded PACF QA/QC standards. The lower limits of quantification varied by element and by sample and are listed in Appendices 2-3. Percent moisture is also presented to permit wet weight to dry weight conversions.

Statistics

Data were censored as follows: if the total number of detections for a metal was below ½ the total number of samples collected, then no statistical analysis was performed for this metal. If the total number of detections was ≥ ½ the total number of samples collected, samples without detections were assigned a value of ½ the limit of detection. Mean trace element were compared among years at individual sites using analysis of variance (ANOVA). The Bonferroni multiple comparison tests (Sokal and Rohlf 1995) were used to test for main effects when Analysis of Variance (ANOVA) showed significant differences. The nonparametric Kruskal-Wallis statistic was used when unequal variances were detected.

RESULTS

Water

Conductivity water quality measurements in 2004 indicated that Beal Lake and the DU Ponds were functioning as pseudo-seeps. However, the DU Ponds were already on groundwater in

2004 and therefore cannot be defined as pseudo-seeps. Prieto (1998) defined pseudo-seeps as having conductivities >1275 and <1790 µS/cm at the surface of the backwater. He also defined connected lakes as backwaters with conductivities <1275 µS/cm and true seeps with conductivities >2000 µS/cm. Mean true seep conductivities according to Prieto (1998) were 9144 µS/cm. Given our conductivity measurements (Appendix 1), we considered Beal Lake and the DU Ponds pseudo-seeps, even though at the DU Ponds this is not technically correct. Their conductivities ranged from 1460-3880 µS/cm, but were never as high as 9144 µS/cm. Although the DU Ponds may have functioned as a pseudo-seep in 2004 when measurements were taken, they were not being supplied with Colorado River water. Therefore, selenium inputs into the DU Ponds were low to non-existent and the term pseudo-seep should not be used for the DU Ponds.

The two reference backwaters, Office Cove and High Levee Pond, were a pseudo-seep and a connected lake, respectively. Office Cove is connected to the Colorado River/Lake Havasu through one semipermeable berm and had conductivities at the surface ranging from 2210-3220 µS/cm but not as high as 9144 µS/cm like a true seep would. Although its conductivities were greater than a true pseudo-seep typically has, Office Cove does not function as a connected lake with one semipermbeable berm, high temperatures, and low DO. High Levee Pond was a connected lake because its conductivities most closely resembled that of the mainstem of the river at 980-1440 µS/cm. The highest conductivities and pHs at High Levee Pond were recorded in September at an unknown time. They water quality measurements recorded at this time are so different from the other two sampling times that we question their validity.

There were no detections of the beryllium, chromium, and lead in any water samples from 2001 or 2004 (Tables 2-5). Cadmium, copper, mercury, molybdenum, nickel, and zinc were infrequently detected. None of the backwaters had selenium concentrations greater than AZ WQS (2003; 0.002 ppm). The highest selenium concentration was 1.1 ppb in one Beal Lake sample from 2001. Some significant differences between 2001 and 2004 were found (Tables 2-5). Mean arsenic concentrations were significantly higher at Beal Lake ($P<0.0001$), Office Cove ($P<0.0001$), and the DU Ponds in 2004 ($P<0.01$). Selenium was significantly higher at Office Cove in 2004 ($P<0.001$), but was significantly lower at the DU Ponds in 2004 ($P<0.01$). Neither increase in arsenic nor selenium was greater than AZ WQS.

Table 2. Water concentrations (ppm, wet weight) at Beal Lake, Havasu NWR, Arizona in 2001 and 2004[1]

	2001					2004		
	AZ WQS[2]	N[3]	Min - Max	Mean ± SD	Median	N	Min - Max	Mean ± SD
Al	NA[4]	6	0.073 - 0.55	0.224 ± 0.198 A[5]	0.115	6	0.05 - 0.11	0.075 ± 0.021 A
As	0.19	6	0.002 - 0.003	0.002 ± 0.0004 A	0.003	6	0.0045 - 0.0076	0.006 ± 0.001 B**
B	NA	6	0.130 - 0.24	0.178 ± 0.048 A	0.18	6	0.44 - 0.72	0.608 ± 0.108 B**
Ba	NA	6	0.114 - 0.167	0.141 ± 0.019 A	0.14	6	0.97 - 0.143	0.117 ± 0.019 A
Fe	NA	6	0.07 - 0.32	0.153 ± 0.111 A	0.09	5	ND[6] - 0.16	0.084 ± 0.004 A
Mg	NA	6	24.6 - 57.4	40.53 ± 14.17 A	41.85	6	85.1 - 154	129.5 ± 26.09 B**
Mn	NA	6	0.005 - 0.028	0.014 ± 0.009 A	0.012	6	0.053 - 0.11	0.071 ± 0.020 B*
Se	0.002	6	0.0003 - 0.0011	0.0006 ± 0.0004 A	0.0005	6	0.0004 - 0.0009	0.0006 ± 0.0002 A
Sr	NA	6	0.845 - 1.86	1.323 ± 0.435 A	1.335	6	2.5 - 3.52	3.147 ± 0.390 B**
V	NA	6	0.001 - 0.0048	0.003 ± 0.002 A	0.002	6	0.02 - 0.0036	0.003 ± 0.0008 A

[1] Beryllium, chromium, molybdenum, lead were not detected in any samples. Cadmium (2004), copper (2004), mercury (2001, 2004), nickel (2004), and zinc (2004) were not detected in enough samples for statistical analysis.
[2] AZ WQS for chronic, warmwater fisheries. There are no AZ WQS for chronic, warmwater fisheries for most of the metals of interest
[3] N = Number of samples with detections. Statistical analysis was not performed for metals with <1/2 detection of the total number of samples collected. For those samples below the detection limit, ½ the detection limit was substituted. The total number of samples was 6 in 2001and 6 in 2004.
[4] NA = Not available.
[5] Letters denote results of statistical tests between years. Two similar letters represents no statistical difference and two different letters represents a statistical difference, resulting in the P-value shown in the last column.
[6] ND = nondetect.
* P-value is 0.0001
** P-value is <0.0001

Table 3. Water concentrations (ppm, wet weight) at Office Cove, Bill Williams River NWR, Arizona in 2001 and 2004[1].

	2001				2004		
	AZ WQS[2]	N[3]	Min - Max	Mean ± SD	N	Min - Max	Mean ± SD
Al	NA[4]	6	0.21 - 0.29	0.242 ± 0.028 A[5]	6	0.13 - 0.24	0.15 ± 0.044 B*
As	0.19	6	0.007 - 0.008	0.007 ± 0.0002 A	6	0.011 - 0.013	0.012 ± 0.0008 B***
B	NA	6	1.5 - 1.6	1.567 ± 0.052 A	6	1.9 - 2	1.917 ± 0.041 B***
Ba	NA	6	0.069 - 0.074	0.072 ± 0.0019 A	6	0.047 - 0.049	0.048 ± 0.0006 B***
Fe	NA	5	ND[6] - 0.09	0.058 ± 0.021 A	6	0.07 - 0.19	0.093 ± 0.048 A
Mg	NA	6	28.2 - 30.1	29.43 ± 0.677 A	6	18.1 - 18.4	18.23 ± 0.103 B***
Mn	NA	6	0.032 - 0.041	0.036 ± 0.003 A	6	0.015 - 0.018	0.016 ± 0.001 B***
Mo[7]	NA	6	0.04 - 0.04	0.04 ± 0 A	6	0.069 - 0.07	0.070 ± 0.0005 B*
Se	0.002	6	0.0002 - 0.0004	0.0003 ± 7.53E-05 A	6	0.0005 - 0.0009	0.0006 ± 0.0001 B**
Sr[7]	NA	6	0.664 - 0.701	0.684 ± 0.016 A	6	0.496 - 0.502	0.500 ± 0.003 B*
V[8]	NA	6	0.0056 - 0.0061	0.009 ± 0.0002 A	6	0.016 - 0.017	0.017 ± 0.0005 B***

[1] Beryllium, chromium, mercury, and lead were not detected in any samples. Cadmium (2004), copper (2004), nickel (2004), and zinc (2001, 2004) were not detected in enough samples for statistical analysis.
[2] AZ WQS for chronic, warm waterfisheries. There are no AZ WQS for chronic, warmwater fisheries for most of the metals of interest.
[3] N = Number of samples with detections. Statistical analysis was not performed for metals with <1/2 detection of the total number of samples collected. For those samples below the detection limit, ½ the detection limit was substituted. The total number of samples was 6 in 2001and 6 in 2004.
[4] NA = Not available.
[5] Letters denote results of statistical tests between years. Two similar letters represents no statistical difference and two different letters represents a statistical difference, resulting in the P-value shown in the last column.
[6] ND = nondetect.
[7] Molybdenum and strontium data were analyzed with nonparametric Kruskal-Wallis statistics.
[8] Vanadium data were log-transformed and statistical tests were performed on log-transformed data. Geometric means for 2001 and 2004 were 0.006 and 0.017, respectively.
* P-value <0.01
** P-value <0.001
***P-value <0.0001

Table 4. Water concentrations (ppm, wet weight) at High Levee Pond, Cibola NWR, Arizona in 2001 and 2004[1].

		2001			2004		
	AZ WQS[2]	N[3]	Min - Max	Mean ± SD	N	Min - Max	Mean ± SD
Al	NA[4]	6	0.03 - 0.33	0.119 ± 0.121 A[5]	6	0.02 - 0.11	0.056 ± 0.032 A
As	0.19	6	0.001 - 0.002	0.002 ± 0.0005 A	6	0.001 - 0.002	0.002 ± 0.0004 A
B	NA	6	0.12 - 0.18	0.157 ± 0.022 A	6	0.2 - 0.22	0.212 ± 0.008 B****
Ba	NA	6	0.102 - 0.139	0.128 ± 0.015 A	6	0.111 - 0.115	0.113 ± 0.001 B*
Mg	NA	6	29.1 - 39.4	36.28 ± 4.258A	6	39.6 - 40.6	40.2 ± 0.374 B**
Mn	NA	6	0.067 - 0.081	0.075 ± 0.006 A	6	0.018 - 0.048	0.033 ± 0.012 B*****
Se	0.002	1	ND[6] - 0.0003	---------	3	ND - 0.0004	-----------
Sr	NA	6	0.934 - 1.29	1.179 ± 0.144 A	6	1.29 - 1.32	1.302 ± 0.010 A
V	NA	6	0.001 - 0.003	0.002 ± 0.0008 A	6	0.003 - 0.004	0.003 ± 0.0003 B***

[1] Beryllium, chromium, mercury, molybdenum, nickel, and lead were not detected in any samples. Cadmium (2004), copper (2001), iron (2001, 2004), selenium (2001, 2004), and zinc (2001, 2004) were not detected in enough samples for statistical analysis.
[2] AZ WQS for chronic, warmwater fisheries. There are no AZ WQS for chronic, warmwater fisheries for most of the metals of interest.
[3] N = Number of samples with detections. Statistical analysis was not performed for metals with <1/2 detection of the total number of samples collected. For those samples below the detection limit, ½ the detection limit was substituted. The total number of samples was 6 in 2001and 6 in 2004.
[4] NA = not available.
[5] Letters denote results of statistical tests between years. Two similar letters represents no statistical difference and two different letters represents a statistical difference, resulting in the P-value shown in the last column.
[6] ND = nondetect.
* P-value=0.04
**P-value=0.05
*** P-value <0.01
**** P-value <0.001
*****P-value <0.0001

Table 5. Water concentrations (ppm, wet weight) at the DU Ponds, Imperial NWR, Arizona in 2001 and 2004[1].

		2001			2004		
	AZ WQS[2]	N[3]	Min - Max	Mean ± SD	N	Min - Max	Mean ± SD
Al	NA[4]	6	0.28 - 1.4	0.625 ± 0.423 A[8]	6	0.05 - 1	0.288 ± 0.370 A
As	0.19	6	0.002 - 0.004	0.003 ± 0.0006 A	6	0.004 - 0.008	0.006 ± 0.002 B*
B	NA	6	0.27 - 0.4	0.337 ± 0.066 A	6	0.51 - 1.5	1.153 ± 0.379 B**
Ba	NA	6	0.11 - 0.173	0.145 ± 0.027 A	6	0.033 - 0.105	0.062 ± 0.025 B**
Cu	0.00896	5	ND[7] - 0.006	0.004 ± 0.002 A	4	ND - 0.004	0.002 ± 0.001 A
Fe[5]	NA	6	0.23 - 0.7	0.465 ± 0.201 A	6	0.07 - 0.32	0.170 ± 0.101 B*
Mg	NA	6	44.6 - 67.5	57.52 ± 10.69 A	6	66.4 - 248	185.4 ± 66.31 B**
Mn	NA	6	0.034 - 0.13	0.079 ± 0.031 A	6	0.0071- 0.18	0.109 ± 0.070 A
Se	0.002	6	0.0004 - 0.0007	0.0006 ± 0.0001 A	6	0.0002 - 0.0004	0.0003 ± 8.16E-05 B*
Sr[6]	NA	6	1.54 - 2.21	1.83 ± 0.295 A	6	1.02 - 3.2	1.988 ± 0.936 A

[1] Beryllium, chromium, molybdenum, and lead were not detected in any samples. Cadmium (2004), mercury (2001, 2004), nickel (2001, 2004), vanadium (2004), and zinc (2001) were not detected in enough samples for statistical analysis.
[2] AZ WQS for chronic, warmwater fisheries. There are no AZ WQS for chronic, warmwater fisheries for most of the metals of interest The chronic copper standard was determined using 100 mg/l calcium carbonate.
[3] N = Number of samples with detections. Statistical analysis was not performed for metals with <1/2 detection of the total number of samples collected. For those samples below the detection limit, ½ the detection limit was substituted. The total number of samples was 6 in 2001and 6 in 2004.
[4] NA = Not available.
[5] Iron data were log-transformed and statistical tests were performed on log-transformed data. Geometric means for 2001 and 2004 were 0.427 and 0.146, respectively.
[6] Strontium data were analyzed with nonparametric Kruskal-Wallis statistics.
[7] ND = nondetect.
[8] Letters denote results of statistical tests between years. Two similar letters represents no statistical difference and two different letters represents a statistical difference, resulting in the P-value shown in the last column.
* P-value <0.01
** P-value <0.001

Sediment

Nineteen trace metals were detected in sediment samples, although mercury was only detected in one sample (Office Cove = 0.1 ug/g dry weight) in 2001 (Tables 6-9). Boron and molybdenum were infrequently detected. Selenium was not detected in enough 2004 Office Cove samples, or in enough 2001 DU Ponds samples for statistical analysis. Lead concentrations exceeded Threshold Effect Concentrations (TECs) from MacDonald et al. (2000) in three samples at Beal Lake in 2001. Arsenic, copper, nickel and zinc concentrations in 2001 and 2004 at Office Cove exceeded TECs. Chromium and lead concentrations in 2001 at Office Cove also exceeded TECs. Fourteen samples met or exceeded the selenium sediment threshold for ecological effects, 2 ppm (Lemly 2002). Two occurred in 2001 at Beal Lake and five occurred in 2004 at Beal Lake, one occurred at Office Cove in 2001 and one at Office Cove in 2004 (17 ppm), and one occurred at High Levee Pond in 2001 and four occurred at High Levee Pond in 2004. Since most of the selenium concentrations in Office Cove in 2004 were below detection, the 17 ppm selenium must be an anomaly (the other sample was detected at 1 ppm). However, we do not believe it was due to laboratory error because analysis of selenium duplicates, spike recoveries, and reference materials had near perfect percent-recoveries.

Only one mean selenium concentration at Beal Lake in 2004 (3.2 ppm) exceeded the selenium threshold value of 2 ppm. The only significant selenium interaction was from Beal Lake, where the mean selenium concentration was significantly greater in 2004 than in 2001 ($P=0.03$). Lead concentrations were significantly greater in 2001 at all four locations. The median manganese concentration was significantly greater in 2004 at the DU Ponds ($P=0.01$). The median concentration at the DU Ponds in 2004, 292 ppm, was over 1.5-times greater than the 2001 median concentration at 179 ppm. These concentrations are still below an internationally derived background manganese concentration of 400 ppm (Buchman 1999). Mean strontium concentrations were greater in 2004 at Beal Lake ($P=0.02$) and the DU Ponds ($P<0.0001$). Mean strontium concentrations from Beal Lake and the DU Ponds were greater than the background concentration of 49 ppm (Buchman 1999).

Table 6. Sediment concentrations (ppm, dry weight) at Beal Lake, Havasu NWR, Arizona in 2001 and 2004[1].

		2001			2004		
	TEC[2]	N[3]	Min - Max	Mean ± SD	N	Min - Max	Mean ± SD
Al[4]	NA	6	2,280 - 15,400	8,442 ± 5,474 A[5]	6	5,960 - 12,300	9,098 ± 2,770 A
As	9.79	6	3.4 - 11	6.117 ± 2.903 A	6	3.9 - 7.3	6.05 ± 1.228 A
Ba	NA	6	130 - 229	183.2 ± 36.40 A	6	170 - 356	245.2 ± 69.64 A
Be	NA	4	ND[6] - 0.73	0.568 ± 0.146 A	6	0.3 - 0.66	0.46 ± 0.152 A
Cd	0.99	6	0.4 - 0.5	0.433 ± 0.052 A	5	ND - 0.6	0.433 ± 0.175 A
Cr	43.4	6	3.3 - 17	10.05 ± 5.830 A	6	6.2 - 14	10.38 ± 3.316 A
Cu	31.6	6	3.2 - 16	9.167 ± 4.950 A	6	6.7 - 14	10.87 ± 2.778 A
Fe	NA	6	4,450 - 17,300	11,400 ± 5,415 A	6	7,030 - 14,200	10,787 ± 2,873 A
Mg	NA	6	4,510 - 12,200	8,818 ± 3,296 A	6	6,850 - 11,300	9,217 ± 1,794 A
Mn	NA	6	170 - 396	301.8 ± 94.04 A	6	244 - 373	313.5 ± 57.21 A
Ni[4]	22.7	4	ND - 10	9.75 ± 0.5 A	6	7 - 10	8.667 ± 1.366 A
Pb[7]	35.8	6	22 - **45**	34.33 ± 9.070 A	6	16 - 23	19.67 ± 3.011 B***
Se	(2)[8]	5	ND - **2.8**	1.58 ± 0.996 A	6	1 - **4.8**	**3.217 ± 1.448** B**
Sr	NA	6	91 - 295	179.8 ± 73.81 A	6	192 - 769	444.8 ± 210.4 B*
V	NA	6	7 - 34	19.25 ± 10.83 A	6	15 - 27	21 ± 4.858 A
Zn	121	6	19 - 66	45.67 ± 20.33 A	6	34 - 63	48.67 ± 12.57 A

[1] Mercury was not detected in any samples. Boron and molybdenum were not detected in enough 2001 samples for statistical analysis.
[2] TEC = Threshold effects concentration from MacDonald et al. 2000.
[3] N = Number of samples with detections. Statistical analysis was not performed for metals with <1/2 detection of the total number of samples collected. For those samples below the detection limit, ½ the detection limit was substituted. The total number of samples was 6 in 2001and 6 in 2004.
[4] Aluminum and nickel data were analyzed with nonparametric Kruskal-Wallis statistics.
[5] Letters denote results of statistical tests between years. Two similar letters represents no statistical difference and two different letters represents a statistical difference, resulting in the P-value shown in the last column.
[6] ND = nondetect.
[7] Statistics were performed on log-transformed lead data. Geometric means for 2001 and 2004 were 33.24 and 19.47, respectively.
[8] There was no TEC for selenium, but Lemly (2002) cited 2 ppm as a ecological guideline value for sediment.
* P-value=0.02
**P-value=0.03
** P-value <0.01

Table 7. Sediment concentrations (ppm, dry weight) at Office Cove, Bill Williams River NWR, Arizona in 2001 and 2004[1].

		2001			2004		
	TEC[2]	N[3]	Min - Max	Mean ± SD	N	Min - Max	Mean ± SD
Al	NA[4]	6	16,000 - 37,000	25,583 ± 8,394 A[5]	6	13,600 - 27,900	21,133 ± 5,628 A
As	9.79	6	11 - **25**	**15.67 ± 5.125** A	6	6.3 - **21**	**12.23 ± 5.497** A
Ba	NA	6	399 - 912	574.2 ± 197.1 A	6	304 - 818	561.8 ± 173.0 A
Be[6]	NA	6	0.88 - 1.9	1.447 ± 0.438 A	6	1 - 1.6	1.267 ± 0.234 A
Cd	0.99	6	0.4 - 0.66	0.51 ± 0.084 A	6	0.2 - 0.74	0.49 ± 0.1715 A
Cr	43.4	6	21 - **44**	31.17 ± 8.931 A	6	16 - 28	23.17 ± 4.491 A
Cu	31.6	6	22 - **64**	**39.33 ± 15.95** A	6	21 - **33**	26.5 ± 5.128 A
Fe	NA	6	24,900 - 40,100	33,033 ± 6,021 A	6	27,200 - 35,400	31,017 ± 3,412 A
Mg	NA	6	13,300 - 17,800	15,483 ± 1,858 A	6	11,100 - 19,400	15,650 ± 2812 A
Mn	NA	6	747 - 1,690	1,248 ± 344.8 A	6	835 - 1,770	1,195 ± 362.0 A
Ni	22.7	6	**24 - 42**	**30.5 ± 7.342** A	6	17 - **28**	**23.83 ± 3.971** A
Pb	35.8	6	**37 - 47**	**42 ± 4.099** A	6	20 - 30	24 ± 4.050 B*
Se	(2)[8]	6	0.8 - **2**	1.05 ± 0.473 A	2	ND[7] - **17**	-----------------
Sr	NA	6	363 - 585	441.7 ± 88.42 A	6	263 - 662	442.2 ± 142.8 A
V	NA	6	38 - 63	53.17 ± 10.68 A	6	42 - 62	50.5 ± 8.735 A
Zn	121	6	97 - **140**	117.8 ± 15.50 A	6	100 - **130**	116.7 ± 12.11 A

[1] Boron (2001), mercury (2001, 2004), molybdenum (2001, 2004), and selenium (2004) were not detected in enough samples for statistical analysis.
[2] TEC = Threshold effect concentration from MacDonald et al. 2000.
[3] N = Number of samples with detections. Statistical analysis was not performed for metals with <1/2 detection of the total number of samples collected. For those samples below the detection limit, ½ the detection limit was substituted. The total number of samples was 6 in 2001and 6 in 2004.
[4] NA = Not available.
[5] Letters denote results of statistical tests between years. Two similar letters represents no statistical difference and two different letters represents a statistical difference, resulting in the P-value shown in the last column.
[6] Statistics were performed on log-transformed beryllium data.
[7] ND = nondetect.
[8] There was no TEC for selenium, but Lemly (2002) cited 2 ppm as a ecological guideline value for sediment.
One sediment sample at Office Cove had a concentration greater than the TEC, at 17 ppm (in bold).
* P-value <0.0001

Table 8. Sediment concentrations (ppm, dry weight) at High Levee Pond, Cibola NWR, Arizona in 2001 and 2004[1].

		2001			2004		
	TPEC[2]	N[3]	Min - Max	Mean ± SD	N	Min - Max	Mean ± SD
Al	NA[4]	6	7,650 - 11,400	9,378 ± 1,222 A[5]	6	4,300 - 12,200	8,163 ± 2,854 A
As	9.79	6	3.9 - 5.9	4.75 ± 0.745 A	6	2.9 - 6.7	4.317 ± 1.419 A
B[6]	NA	4	ND[7] - 10	8.333 ± 2.582 A	5	ND - 20	16 ± 5.477 A
Ba	NA	6	117 - 199	156. 7 ± 28.93 A	6	94.8 - 275	168.3 ± 64.04 A
Be	NA	6	0.4 - 0.5	0.45 ± 0.055 A	6	0.2 - 0.6	0.433 ± 0.151 A
Cr[6]	43.4	6	10 - 13	11 ± 1.095 A	6	5.1 - 14	10.08 ± 3.476 A
Cu	31.6	6	6.5 - 11	8.05 ± 1.933 A	6	3.6 - 12	8.533 ± 3.175 A
Fe	NA	6	8,220 - 12,900	10,505 ± 1,619 A	6	5,590 - 12,400	9,873 ± 2617 A
Mg	NA	6	6,640 - 9,520	8,057 ± 1,228 A	6	4,730 - 10,200	7,666 ± 2,083 A
Mn	NA	6	280 - 445	370. 7 ± 70.20 A	6	245 - 502	361.5 ± 86.80 A
Ni	22.7	6	7 - 9	7.667 ± 3 A	5	ND - 10	8.4 ± 1.817 A
Pb	35.8	6	24 - 34	29.17 ± 3.488 A	6	10 - 20	13.33 ± 5.164 B*
Se	(2)[8]	6	0.7 - **2**	1.033 ± 0.493 A	6	1 - **2**	1.667 ± 0.516 A
Sr	NA	6	201 - 673	356 ± 167.3 A	6	248 - 619	412 ± 127.9 A
V	NA	6	16 - 23	21.17 ± 2.639 A	6	10 - 26	19.5 ± 6.285 A
Zn	121	6	29 - 44	35 ± 6.132 A	6	18 - 50	36.33 ± 11.69 A

[1] Mercury and molybdenum were not detected in any samples. Cadmium (2001) was not detected in enough samples for statistical analysis.
[2] TEC = Threshold effect concentration from MacDonald et al. 2000.
[3] N = Number of samples with detections. Statistical analysis was not performed for metals with <1/2 detection of the total number of samples collected. For those samples below the detection limit, ½ the detection limit was substituted. The total number of samples was 6 in 2001and 6 in 2004.
[4] NA = Not available.
[5] Letters denote results of statistical tests between years. Two similar letters represents no statistical difference and two different letters represents a statistical difference, resulting in the P-value shown in the last column.
[6] Statistics were performed on log-transformed boron and chromium data.
[7] ND = nondetect.
[8] There was no TEC for selenium, but Lemly (2002) cited 2 ppm as a ecological guideline value for sediment.
* P-value <0.0001

Table 9. Sediment concentrations (ppm, dry weight) at the DU Ponds, Imperial NWR, Arizona in 2001 and 2004[1].

		2001			2004		
	TEC[2]	N[3]	Min - Max	Mean ± SD	N	Min - Max	Mean ± SD
Al	NA[4]	6	2,700 - 8,710	4,720 ± 2,426 A[5]	6	2,700 - 7,510	4,888 ± 1,942 A
As	9.79	6	1 - 4.2	2.283 ± 1.010 A	6	1.9 - 3.9	3.333 ± 0.763 A
Ba	NA	6	102 - 175	136.8 ± 31.52 A	6	131 - 305	199.8 ± 63.88 A
Cd	0.99	5	ND - 0.4	0.267 ± 0.103 A	4	ND - 0.6	0.317 ± 0.194 A
Cr	43.4	6	3.8 - 9.9	6.117 ± 2.306 A	6	3.7 - 9.4	6.367 ± 2.177 A
Cu	31.6	5	ND - 8.6	3.567 ± 3.051 A	6	3 - 8	6 ± 1.663 A
Fe	NA	6	3,900 - 10,100	6,100 ± 2,359 A	6	4,410 - 8780	7,276 ± 1,645 A
Mg	NA	6	3,470 - 8,700	5,546 ± 2,115 A	6	5,580 - 9,170	7,370 ± 1,275 A
Mn[6]	NA	6	130 – 260	183.7 ± 54.66 A	6	242 - 305	279 ± 28.04 B*
Pb[6]	35.8	6	10 - 27	17.67 ± 6.9472 A	6	9 - 15	10.67 ± 2.160 B**
Se	(2)[8]	1	ND - 0.5	----------------	5	ND - 1	0.917 ± 0.204
Sr[7]	NA	6	60 - 138	101.8 ± 27.82 A	6	323 - 661	524.5 ± 141.9 B***
V	NA	6	6.7 - 18	11.2 ± 4.102 A	6	7.8 - 19	12.82 ± 4.291 A
Zn	121	6	11 - 39	20.17 ± 10.94 A	6	14 - 35	27.67 ± 7.448 A

[1] Mercury and molybdenum were not detected in any samples. Boron (2001), beryllium (2001), nickel (2001), and selenium (2001) were not detected in enough samples for statistical analysis.
[2] TEC = Threshold effect concentration from MacDonald et al. 2000.
[3] N = Number of samples with detections. Statistical analysis was not performed for metals with <1/2 detection of the total number of samples collected. For those samples below the detection limit, ½ the detection limit was substituted. The total number of samples was 6 in 2001 and 6 in 2004.
[4] NA = Not available.
[5] Letters denote results of statistical tests between years. Two similar letters represents no statistical difference and two different letters represents a statistical difference, resulting in the P-value shown in the last column.
[6] Nonparametric statistics (Kruskal-Wallis) were used on manganese and lead. Median manganese concentrations in 2001 and 2004 were 179 and 292 ppm, respectively. Median lead concentrations in 2001 and 2004 were 18 and 10 ppm, respectively.
[7] Statistics were performed on log-transformed strontium data. Geometric means for 2001 and 2004 were 98.34 and 507.1, respectively.
[8] There was no TEC for selenium, but Lemly (2002) cited 2 ppm as a ecological guideline value for sediment.
* P-value=0.01
**P-value=0.04
*** P-value <0.0001

Although we examined the difference in metal concentrations in water and sediment at each backwater between years, we only compared selenium in water in reference backwaters versus experimental backwaters. In 2001, Beal Lake and the DU Ponds selenium concentrations were similar to each other and statistically greater than Office Cove selenium concentrations (X^2=0.0372) (Figure 5). Beal Lake and Office Cove selenium concentrations were more similar to each other and greater than the DU Ponds in 2004 (X^2=0.0036). This could reflect the change in water management at the DU Ponds, as the Refuge managers switched from using lower Colorado River water to groundwater. There was not enough selenium detected in High Levee Pond water samples for statistical analysis.

We also compared sediment in reference backwaters with the experimental backwaters and found no significant difference between selenium concentrations in Beal Lake and High Levee Pond in 2001 (Figure 6). However, there was a significant difference in selenium concentrations in sediment between Beal Lake and High Levee Pond in 2004 (P=0.033). Office Cove and the DU Ponds were not used in this comparison because selenium was not detected in enough samples for statistical analysis.

While some metal concentrations increased over time at individual backwaters (e.g., magnesium and manganese increased in water at Beal Lake), trends in other metals showed decreasing concentrations over time (e.g., aluminum and boron decreased in water at Office Cove). Although selenium increased in water at Office Cove and increased in sediment at Beal Lake, more samples would need to be collected to determine if a trend in either water or sediment selenium concentrations is occurring.

Figure 5. Selenium concentrations (ppm, wet weight) in water between Beal Lake, the DU Ponds, and Office Cove in 2001 and 2004. Comparisons are within years only. Bar graphs represent mean water concentrations.

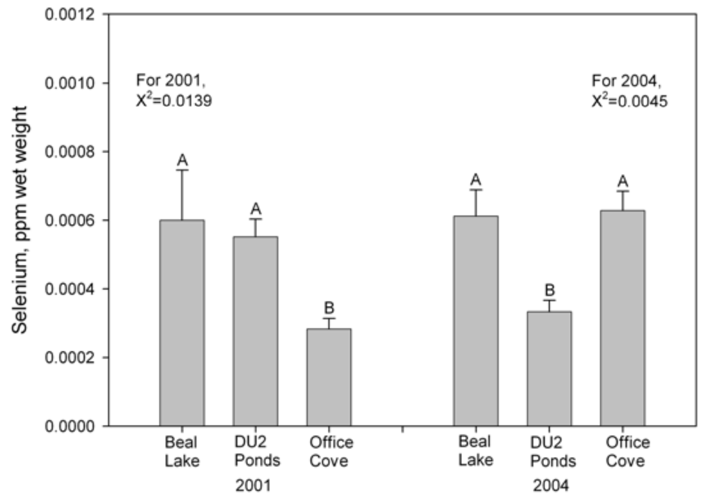
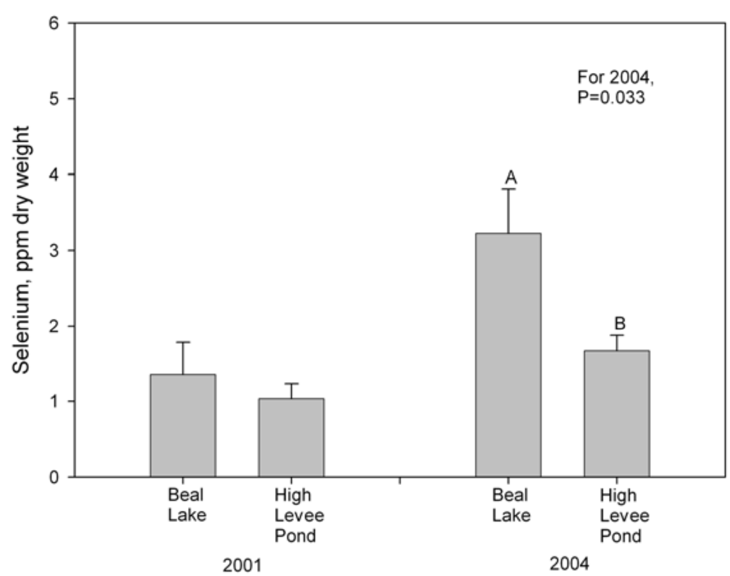


Figure 6. Selenium concentrations (ppm, dry weight) in sediment between Beal Lake and High Levee Pond in 2001 and 2004. Comparisons are within years only. Bar graphs represent mean sediment concentrations.



Invertebrates

There was only one invertebrate composite sample per backwater due to the small mass of the invertebrates and the quantity required to accumulate enough mass for analyses. No mercury was detected in any samples and beryllium, molybdenum, and selenium were not detected in enough samples for statistical analysis (Table 10). Greater concentrations of aluminum, chromium, iron, and manganese in 2004 could be attributed to differences in species composition in 2001 and 2004. Selenium was detected in 2001 samples and the highest selenium invertebrate sample was 4.4 ppm dry weight from Beal Lake. This concentration is greater than the 3 ppm dry weight dietary effect level for invertebrates (Lemly 1996). This is the concentration at which adverse effects may occur if another species consumes the invertebrates (Seiler et al. 2003). Although all backwater area data were pooled in 2001, the mean invertebrate selenium concentration was greater than mean crayfish selenium concentrations in individual backwater data in 2001. Statistical analysis on other metals revealed significant differences in 2001 and 2004 in aluminum, chromium, iron, and manganese. All of these differences were the result of higher mean concentrations in the 2004 samples.

Table 10. Invertebrate concentrations (dry weight, ppm) at the Lower Colorado River Refuges, Arizona in 2001 and 2004[1].

	2001[2]			2004[3]		
	N[4]	Min - Max	Mean ± SD	N	Min - Max	Mean ± SD
Al	4	796 – 2,260	1,185 ± 717.8 A[5]	3	2,470 – 6,070	4,070 ± 1,833 B*
As	4	1.6 - 5	3.28 ± 1.676 A	3	3.1 - 7.2	5.1± 2.052 A
B	4	3 - 38	12.3 ± 17.17 A	3	15 - 100	45.7 ± 47.18 A
Ba	4	33.4 - 113	75.2 ± 43.28 A	3	101 - 232	161 ± 66.11 A
Cd	3	ND[6] - 0.53	0.22 ± 0.216 A	2	ND - 0.7	0.417 ± 0.333 A
Cr	4	0.6 - 2.4	1.23 ± 0.802 A	3	2.9 - 5.4	3.87 ± 1.343 B*
Cu	4	12 - 25	19 ± 6.481 A	3	8.5 - 20	13.8 ± 5.795 A
Fe	4	780 - 2,440	1,312 ± 767.2 A	3	3,420 - 6,970	4,907 ± 1,843 B*
Mg	4	1,650 - 6,400	3,048 ± 2,257 A	3	2,750 - 15,500	7,703 ± 6,834 A
Mn	4	83.3 - 127	109 ± 18.34 A	3	258 - 445	333 ± 98.84 B**
Ni	3	ND - 1.9	0.988 ± 0.686 A	3	1.8 - 5.1	2.9 ± 1.905 A
Pb	4	1.2 - 4.1	2 ± 1.407 A	3	2.7 - 7.5	5.5 ± 2.498 A
Se	4	1 - **4.4**	2.5 ± 1.417 A	1	ND - 1	-------------
Sr	4	187 - 1,220	608 ± 505.6 A	3	460 - 784	670 ± 181.8 A
V	4	1.9 - 8.8	4.73 ± 3.069 A	3	5.8 - 58	25.3 ± 28.52 A
Zn	4	36 - 86.4	59.7 ± 21.21 A	3	53.6 - 57.8	55.6 ± 2.113 A

[1] Mercury was not detected in any samples. Beryllium (2001), molybdenum (2001, 2004), and selenium (2004) were not detected in enough samples for statistical analysis.
[2] Invertebrate samples were collected at Beal Lake, Office Cove, High Levee Pond, and the DU Ponds and pooled for analysis.
[3] Invertebrate samples were collected at Beal Lake, Office Cove, and High Levee Pond and pooled for analysis.
[4] N = Number of samples with detections. Statistical analysis was not performed for metals with <1/2 detection of the total number of samples collected. For those samples below the detection limit, ½ the detection limit was substituted. The total number of samples was 4 in 2001 and 3 in 2004.
[5] Letters denote results of statistical tests. Two similar letters represents no statistical difference and two different letters represents a statistical difference, resulting in the P-value shown in the last column.
[6] ND = nondetect.
* P-value <0.1
** P-value <0.01
Bold values were greater than the 4-5 ppm moderate selenium hazard summarized in Lemly 1995. This data was collected at Beal Lake in 2001.

Crayfish

No crayfish were available from the Bill Williams River in 2004. Therefore, statistical analysis only considered difference between metals at each backwater in 2001, not including the reference samples from the Bill Williams River. No beryllium or molybdenum was detected in any crayfish samples (Table 11). Mercury and nickel were not detected in enough samples for statistical analysis. Reference concentrations from crayfish collected after depuration but before deployment in *in-situ* cages were from below detection to 0.4 ppm dry weight selenium. Concentrations of selenium in exposed crayfish ranged from 0.4 ppm at High Levee Pond to 2.0 ppm at the DU Ponds. None of the selenium concentrations exceeded the 3 ppm dietary effect level for invertebrates (Lemly 1996). Statistical differences were detected for boron and selenium between different backwaters. For example, boron concentrations were highest at Office Cove and statistically greater than all other backwaters. Selenium concentrations were highest at the DU Ponds (Colorado River water was used in 2001) and Beal Lake and were statistically greater than selenium concentrations from Office Cove and High Levee Pond.

Table 11. Crayfish whole body concentrations (dry weight, ppm) at Beal Lake, Office Cove, High Levee Pond, and DU Ponds, Arizona in 2001[1] and in crayfish direct from the Bill Williams River.

	2001 BWR Ref[2]		2001 Beal Lake		2001 Office Cove		2001 High Levee Pond		2001 DU Ponds	
	N[3]	(Min – Max) Mean ± SD	N	(Min – Max) Mean ± SD	N	(Min – Max) Mean ± SD	N	(Min – Max) Mean ± SD	N	(Min – Max) Mean ± SD
As	2	(1.7 - 3.1)	4	(2.3 -2.8)	5	(1.3 - 2.6)	6	(1.2 - 2)	4	(1.7 - 3.4)
		2.4 ± 0.99		2.5 ± 0.22 A[4]		1.64 ± 0.55 A		1.65 ± 0.28 A		2.23 ± 0.81 A
B	2	(5 - 6.5)	4	(4 -5)	5	(8.5 - 9.5)	6	(3 - 5)	4	(4 - 6.4)
		5.75 ± 1.06		4.8 ± 0.5 A		9.1 ± 0.47 B****		3.83 ± 0.85 AC****		4.85 ± 1.14 ACD***
Ba	2	(386 - 1,196)	4	(399 - 508)	5	(318 - 489)	6	(308 - 498)	4	(212 - 566)
		788 ± 569		467 ± 50.9 A		432 ± 69.6 A		404 ± 62.1 A		375 ± 146 A
Cd	1	(ND[5] - 0.2)	4	(0.2 - 0.5)	5	(0.2 - 0.42)	6	(0.2 - 0.31)	4	(0.1 - 0.32)
		NA[6]		0.34 ± 0.12 A		0.34 ± 0.11 A		0.24 ± 0.05 A		0.21 ± 0.09 A
Cr	1	(ND – 1)	3	(ND - 2.7)	1	(ND - 0.6)	4	(ND - 2)	2	(ND - 0.7)
		NA		1.19 ± 1.06 A		NA		0.78 ± 0.66 A		NA
Cu	2	(75.2 - 122)	4	(133 – 164)	5	(110 - 213)	6	(45.5 - 152)	4	(62.4 – 137)
		98.6 ± 33.1		151 ± 14.1 A		147 ± 38.9 A		101 ± 26.8 A		102 ± 33.1 A
Mn	2	(201 - 525)	4	(171 – 416)	5	(212 - 917)	6	(162 - 581)	4	(113 - 323)
		363 ± 229		321 ± 110 A		464 ± 269 A		306 ± 149 A		217 ± 92.2 A
Ni	1	(ND - 1)	2	(ND – 1)	2	(ND - 0.8)	0	ND	1	(ND - 0.8)
		NA		NA		NA		NA		NA
Pb	2	(0.83 - 3.1)	4	(0.67 - 1.9)	5	(0.6 - 1.5)	6	(0.2 - 0.84)	4	(0.4 - 0.76)
		1.97 ± 1.61		1.09 ± 0.57 A		0.87 ± 0.37 A		0.57 ± 0.21 A		0.57 ± 0.16 A
Se	1	(ND - 0.4)	4	(0.91 - 1.6)	5	(0.5 - 0.75)	6	(0.4 - 0.81)	4	(0.83 – 2)
		NA		1.33 ± 0.31 A		0.64 ± 0.10 B**		0.65 ± 0.15 B**		1.36 ± 0.48 AC*
Zn	2	(95 – 149)	4	(78.1 - 87.6)	5	(78 - 105)	6	(58.7 - 92.1)	4	(76.5 – 149)
		122 ± 38.2		84.5 ± 4.38 A		89.4 ± 11.3 A		75.8 ± 13.8 A		95.5 ± 35.7 A

[1] No beryllium or molybdenum was detected in any samples. Mercury and nickel were not detected in enough samples for statistical analysis.
[2] BWR Ref = Bill Williams River Reference crayfish samples. Crayfish were originally collected from the Bill Williams River, allowed to depurate for two weeks in the lab and then placed in the field at the other backwaters for one month. These samples were allowed to depurate for 2 weeks in the lab and then were set aside for analysis. Also, these samples were not used in statistical analyses because of the low sample size.
[3] N = Number of samples with detections. Statistical analysis was not performed for metals with <1/2 detection of the total number of samples collected. For those samples below the detection limit, ½ the detection limit was substituted. Total number of samples collected can be found in Appendix 2.
[4] Similar letters are statistically similar and dissimilar letters are statistically different. *P>0.1; **P>0.01; ***P>0.001; ****P>0.0001
[5] ND = Non detect.
[6] NA = Not available because of lack of data for statistical analysis.

Fish

Seventeen trace elements were detected in whole body razorback suckers (Table 12). Whole body fish samples were collected in 2002 from a stocking event at Beal Lake (n=11 razorbacks). Razorback suckers were again stocked into the DU Ponds in 2004 after the 2001 effort failed. We did not collect any whole body razorback suckers after they had been in Beal Lake or the DU Ponds for greater than one year. The fish stocked at Beal Lake were most likely consumed within a week of release by fish-eating birds. We did not have enough time to collect samples after the 2004 stocking at the DU Ponds because our field work for this study was completed.

The razorback suckers used for stocking came from wild larvae captured in Lake Mohave and reared at Willow Beach National Fish Hatchery, Arizona which is just below the Hoover Dam on the lower Colorado River. Fish were reared at the hatchery until around 100 mm total length when they were ready for release into isolated backwaters. Male razorback suckers at this length are reproductively mature (Chester Fiegel, pers. comm.). Selenium concentrations in fingerling razorback suckers ranged from 0.93-1.5 ppm dry weight in 2002 and 1.8-4.0 ppm dry weight in 2004. Selenium was statistically greater in 2004 than in 2002. One whole body fish from 2004 met the 4 ppm threshold for juvenile mortality and adult reproductive impairment (Lemly 1996, Hamilton 2002). Arsenic, barium, copper, iron, manganese, and strontium concentrations were statistically higher in 2002 than in 2004.

It was our intention to re-sample these same fishes after they had resided in the isolated backwaters for more than one year, but pond management was not as successful as we had hoped and we did not have the opportunity to sample from the same populations again for post-manipulation analyses. It is possible that the hatchery feed supplied to the razorback suckers contributed to higher whole body metal concentrations in 2002 than in 2004 (except for zinc) although we do not have any information regarding metal concentrations in feed. If this was the case, then arsenic and copper may not be contaminants of concern on the lower Colorado River.

Razorback sucker muscle plugs were collected from adult fish that had been in the DU Ponds for at least a year in December 2003 (Table 13). Fisheries biologists collected all the razorback suckers in the DU Ponds with trammel nets prior to a renovation at the site. No selenium was detected in the razorback sucker muscle plugs. Mercury was detected in one razorback sucker muscle plug from the DU Ponds at 1 ppm, which is 3-times greater than the fish tissue criterion (fillet) of 0.3 ppm methylmercury established by the US EPA in 2001. This criterion was developed to be protective of humans consuming fish and is the level at which mercury fish advisories are established around the nation (US EPA 2001).

Other individual fish were collected with dip net and seine (mosquitofish) or salvaged from nets during routine monitoring (bonytails) (Table 14). Mosquitofish were collected at West Meander at Cibola NWR when it was considered as another potential isolated native fish habitat. Mosquitofish were composited into one sample. The selenium concentration in mosquitofish was greater than the NCBP 85th percentile and the 4 ppm threshold for whole body fish tissues established to protect juveniles from mortality and adults from reproductive failure (Lemly 1996, 1993, Hamilton 2002). One bonytail had a selenium concentration greater than the NCBP 85th

percentile, but lower than the threshold for reproductive failure. Compared to other selenium concentrations in fish on the lower Colorado River, the mosquitofish sample was most like selenium concentrations detected at Cibola Lake at Imperial NWR (5.2-5.6 ppm dry weight) and the bonytails were most like the Palo Verde Outfall Drain samples at Cibola NWR (2.48-3.44 ppm dry weight) (Radtke et al. 1988).

Other metals that were detected in mosquitofish greater than the NCBP 85th percentile were arsenic (1.2 ppm) and zinc (181 ppm). Copper was detected at concentrations greater than the NCBP 85th percentile in two bonytails from Lake Havasu (Table 14). One bonytail had 304 ppm copper in whole body tissues.

Table 12. Razorback sucker whole body concentrations (dry weight, ppm) in fish direct from the hatchery, pre-stocking at Beal Lake, Havasu NWR in 2002 and the DU Ponds, Imperial NWR, Arizona in 2004[1]. The DU Ponds were stocked in 2001, were infested with non-natives and renovated in 2003, and re-stocked in 2004. We sampled the fish re-stocked in 2004.

		2002			2004		
	NCBP[2] 85th Percentile	N[3]	Min - Max	Mean ± SD	N	Min - Max	Mean ± SD
Al	NA[4]	11	21 - 120	63.55 ± 31.52 A[5]	10	11 – 74	44.20 ± 20.47 A
As	1.08	11	1.1 - **2.8**	**1.77** ± 0.50 A	10	0.5 - 0.82	0.70 ± 0.10 B***
Ba	NA	11	2 – 5.6	3.50 ± 1.08 A	10	0.2 - 0.68	0.40 ± 0.14 B***
Cu	4	11	3.2 – **5.5**	3.94 ± 0.64 A	10	2.6 – **4.3**	3.03 ± 0.51 B**
Fe	NA	11	98 - 423	194.7 ± 92.44 A	10	34 – 87	54.7 ± 17.43 B***
Mg	NA	11	1,020 – 1,430	1,237 ± 122.4 A	10	816 – 1,050	948.4 ± 72.17 B***
Mn	NA	11	15 - 40.09	51.03 ± 43.93 A	10	1 – 3.2	1.73 ± 0.66 B***
Se[6]	2.92	11	0.93 - 1.50	1.16 ± 0.15 A	10	1.8 – **4.0**	2.47 ± 0.77 B***
Sr	NA	11	163 - 286	222.1 ± 33.25 A	10	97.4 – 159	121.6 ± 22.19 B***
Zn	136.8	11	84.4 - **141**	118.2 ± 17.44 A	10	114 - **189**	**148.9** ± 25.56 B**

[1] Beryllium and molybdenum were not detected in any samples. Boron (2002, 2004), cadmium (2002, 2004), chromium (2004), mercury (2002, 2004), nickel (2002, 2004), lead (2002, 2004), and vanadium (2004) were not detected in enough samples for statistical analysis. The remaining metals were all log-transformed for statistical analysis. Bold numbers indicate concentrations greater than the NCBP 85th percentile.

[2] NCBP data from Schmitt and Brumbaugh (1990). Wet weight concentrations were converted to dry weight using 75% moisture content.

[3] N = Number of samples with detections.

[4] NA = Not available.

[5] Letters denote results of statistical tests. Two similar letters represents no statistical difference and two different letters represents a statistical difference, resulting in the P-value shown in the last column.

[6] Nonparametric statistics (Kruskal-Wallis) were used on selenium. Medians for 2001 and 2004 were 1.15 and 2.1, respectively.

* P-value <0.1

** P-value <0.01

*** P-value <0.0001

Table 13. Muscle plug concentrations from razorback suckers at the DU Ponds in 2003 (ppm, dry weight).

	Comparison Data	2003 DU Ponds Razorback Sucker Muscle Plugs[1]
% Moisture		*12* 63.6 ± 11.1 (33.3 - 73.5)
Al		*12* 59.3 ± 48.2 (20 - 190)
As		*0* (ND)
Ba		*12* 4.58 ± 4.92 (2 - 19)
Cr		*12* 26.5 ± 37.3 (1 - 113)
Cu		*11* 1.43 ± 0.92 (0.7 - 3.7)
Fe		*12* 593 ± 637 (39 -1,600)
Hg	0.3 ppm[2]	*1* (ND - **1**)
Mg		*12* 983 ± 193 (600 - 1,400)
Mn		*12* 7.9 ± 6.54 (0.7 - 24)
Ni		*9* 196 ± 374 (ND - 1,230)
Pb		1 (ND - 4)
Se	3.4 ppm[3]	0 (ND)
Sr		*12* 66.6 ± 54.7 (2.3 - 17)
V		*3* (ND – 2)
Zn		*12* 39 ± 70.5 (77.2 - 346)

[1]*N* (= number of detections) Mean ± SD (range)
[2] Recommended human consumption advisory limit for methylmercury in fish fillets (EPA 2001).
[3] In a dorsal muscle plug from a razorback sucker in Waddell and May (2000).

Table 14. Fish whole body concentrations (dry weight, ppm) at Cibola NWR's West Meander in 2001 and Lake Havasu in 2004[1] and muscle plug concentrations from razorback suckers at the DU Ponds in 2003.

		2001 West Meander	2004 Mainstem Lake Havasu	
	NCBP[2] 85th Percentile	Mosquitofish	Bonytail Chub	Bonytail Chub
% Moisture		68.3	68.3	70.2
Al	NA[3]	130	59	39
As	1.08	**1.2**	0.93	0.74
Ba	NA	20	11	9.8
Cr	NA	6	1	1
Cu	4	3.3	**4.8**	**304**
Fe	NA	190	88	85
Hg	0.68	ND[4]	0.1	0.2
Mg	NA	2,230	1,050	1,090
Mn	NA	28	9.4	10
Ni	NA	2.4	0.7	4.5
Pb	NA	1.6	ND	ND
Se	2.92	**6.1**	2.4	**3**
Sr	NA	232	150	141
V	NA	0.6	1	2.2
Zn	136.8	**181**	79.4	80.8

[1] Boron, beryllium, cadmium, and molybdenum were not detected in any West Meander or Lake Havasu samples. Cadmium was detected in five DU samples, ranging from 0.4 to 1.4 ppm.
[2] NCBP data from Schmitt and Brumbaugh (1990). Wet weight concentrations were converted to dry weight using 75% moisture content. 3 NA = Not available. 4 ND = not detected.

DISCUSSION

Early and Late Post-Manipulation Sampling

Several studies have evaluated the effectiveness of flushing backwater channels on the Colorado River. Selenium sediment and fish concentrations did not dependably diminish after three intermittent flushings of the 243-hectare Cibola Lake, Cibola NWR (Villegas 1997). Villegas (1997) also found that flushing Mittry Lake at Imperial NWR reduced selenium concentrations in sediment and fish to the lower end of the range of selenium concentrations found at Cibola Lake. Hamilton et al. (2004) recently studied backwater flushing and its effect on selenium dynamics and found that flushing effectively reduced selenium in sediment and fish, although they attributed it to the continuous flushing it received and its long, narrow backwater channel design.

In 2002, the DU Ponds were determined to be colonized by non-native fishes after barriers were proven ineffective. Therefore, implementation of the isolated native fish habitat on the lower Colorado River has been delayed. Early and late post-manipulation comparisons were made, but we caution against drawing many conclusions from them. Delays have occurred due to backwater design, inability to keep non-native fish out of the backwaters, and predation on stocked razorback suckers.

Trace Elements in Water, Sediment, Macroinvertebrates, and Fishes over Time

Selenium

Selenium dynamics in the lower Colorado River are influenced by the source of the water, the dynamics of the flow and the backwater's residence time, and the degree of connectivity each backwater has to the mainstem. Our study was unable to determine the exact flow rates of each backwater, but we did characterize each backwater per Prieto's (1998) definitions. Beal Lake and Office Cove were pseudo-seeps. High Levee Pond was a connected lake. We cannot officially characterize the DU Ponds as pseudo-seeps, even though they had characteristics similar to pseudo-seeps, because groundwater was the source of its water, not river water. Besides defining each backwater we studied as a connected lake, pseudo-seep, or true seep, we also analyzed selenium dynamics and how they varied depending on the backwater.

For example, at Imperial NWR, selenium concentrations in fish declined with decreasing connectivity to the mainstem of the river (Prieto 1998). Although we had some variation in selenium concentrations in fishes, none of the sites where fish tissue was collected were thoroughly examined in our study. All of the meaningful selenium data we collected in fishes came from West Meander, Lake Havasu, or the mainstem of the river at Willow Beach National Fish Hatchery. The only fish tissue data we had from fishes that had been in a backwater for approximately one year were the muscle plug data. No selenium was detected in these samples, so we cannot make any conclusions because our data were not robust.

Although our crayfish data were limited, our conclusions did not always agree with Prieto (1998).

Crayfish at Imperial NWR had higher concentrations of selenium in connected lakes than in pseudo-seeps (Prieto 1998). Selenium concentrations in our study were greatest at Beal Lake and the DU Ponds and lowest at Office Cove and High Levee Pond. There could be two explanations as to why our data differed from the Imperial NWR data. Our data was collected from four different refuges along the mainstem, and Prieto (1998) focused all of his work exclusively on the Imperial NWR. Another explanation is that the size of the backwater influenced the amount of selenium available for biotransfer. Office Cove and High Levee Pond are significantly smaller than Beal Lake and the DU Ponds.

None of the mean crayfish selenium concentrations were as high as the 4-5 ppm moderate selenium contamination threshold (Lemly 1995). Selenium accumulation in crayfish at Office Cove and High Levee Pond was lower than in Beal Lake and the DU Ponds (Table 11). Ruiz (1993) found that selenium concentrations in crayfish from the Bill Williams River NWR were higher than the concentrations we detected (1.77 vs. 0.64 ppm dry weight) even though her collections were from crayfish living on the Bill Williams River and our crayfish were only exposed for one month. Selenium concentrations in crayfish from Ruiz (1993) were closer to our values at Beal Lake and the DU Ponds than those at Office Cove or High Levee Pond. Prieto (1998) found selenium concentrations from 1.75-2.4 ppm dry weight in connected lakes and pseudo seeps at Imperial NWR after only seven weeks exposure. These concentrations are only slightly greater than our concentrations at the DU Ponds. It is also possible that we found greater selenium bioaccumulation at Beal Lake and the DU Ponds because they are much larger than the two reference backwaters (at least an order of magnitude larger) and water management between all four backwaters differed.

Selenium was at least 1.6-times greater in the *in-situ* crayfish collected from Office Cove compared to reference crayfish from the Bill Williams River and, at most, 5-times greater in the *in-situ* crayfish from the DU Ponds. The highest mean selenium crayfish concentrations were detected from Beal Lake and the DU Ponds. Previous studies have acknowledged that backwaters such as Beal Lake and the DU Ponds on the lower Colorado River have a greater potential for higher selenium contamination (Lusk 1993, King et al. 1993, Radtke et al. 1988, and McCaulou 1993). Since the water management at the DU Ponds has changed, it is possible that this is no longer the case there. Depending on the type of system that is going to be installed and the rate of water turnover, lack of flushing could still contribute to a collapse of the fishery as the DU Ponds begin to function more like seepage lakes. Selenium should not continue to be a concern there. Continued monitoring is definitely warranted at Beal Lake since selenium concentrations were higher in sediment, water, and crayfish than in other backwater sites. Whether selenium dynamics at Beal Lake were a result of its functioning as pseudo-seep is unknown. Perhaps its lack of connectivity from the mainstem has contributed to increased selenium concentrations. It is also possible that sediment dredging in 2001 to prepare the lake for the native fishery mobilized selenium into the water and biota.

Our results do not agree with other conclusions Prieto (1998) made as well. Prieto (1998) concluded that connected lakes had the highest selenium concentrations in biota because connected backwaters have more fine-grained sediments that act as a sink for selenium, periodic water inflows introduce new fine-grained sediments to backwaters, which reduce selenium concentrations, and connected backwaters receive a constant supply of selenium-laden water as opposed to periodic pulses of water that pseudo-seeps receive. All of our backwaters were connected to the mainstem of the lower

Colorado River, but none received water laden with sediments, because they all had semipermeable berms installed to keep sediment and non-native fishes out of the backwaters. The backwaters we studied may have had more fine-grained sediments to begin with, but they do not receive constant or periodic inflows of sediment. High Levee Pond, the one connected lake we sampled, does receive a constant flow of selenium-laden water, yet selenium concentrations in crayfish there were lower than at Beal Lake and the DU Ponds. Again, it is possible that the size of the backwater influenced the selenium dynamics in crayfish in the backwaters that we sampled. Also, water delivery structures could influence selenium loading as a function of residence time and backwater size.

Although each backwater had at least one semipermeable berm filtering water into and out of the backwater, the water delivery method from the mainstem varied at each backwater. For example, Beal Lake has a long inlet canal that delivers water from Topock Marsh through a semipermeable berm into Beal Lake. The same type of structure also removes water from Beal Lake, after passing through a semipermeable berm, to the mainstem. Office Cove only has one semipermeable berm, which serves as both the inlet and the outlet levee through which water moved. High Levee Pond has a semipermeable berm that water filters through directly into the backwater and a similar berm that water filters out of on the downstream side. There are no delivery canals or structures at either Office Cove or High Levee Pond. Water filtered directly from the source to the backwater through the semipermeable berm. The DU Ponds had a short water delivery structure and then a semipermeable membrane that water filtered through in 2001. As of 2004, water was pumped from the groundwater directly into Pond 1. While each backwater used a semipermeable berm or filter to keep out sediment and non-native fish, the use of the berm varied at each site. It is possible that water delivery structures also influenced connectivity to the mainstem and therefore selenium dynamics at each site.

Selenium concentrations in water and sediment differed at each backwater, independent of whether the backwater was a connected lake or a pseudo-seep. None of the water samples exceeded the Arizona Water Quality Standard for chronic exposures (2 ppb) (AZWQS 2003). Office Cove was the only backwater to exhibit a significant increase in selenium in water from 2001 to 2004. Beal Lake was the only backwater that had a significant increase in selenium concentrations in sediment over time. Fourteen samples from all but the DU Ponds met or exceeded 2 ppm dry weight, the sediment threshold above which ecological effects may occur (Lemly 2002). Overall, there was no clear distinction in water and sediment concentrations of selenium at Beal Lake and the DU Ponds versus Office Cove and High Levee Pond. Selenium concentrations in water and sediment did not follow the same pattern that bioaccumulation in crayfish did. We are not sure why water and sediment had higher selenium concentrations at Beal Lake. It could have to do with its size, the way water has to travel a longer distance from its source (mainstem → inlet canal →Topock Marsh → inlet canal → Beal Lake), the turnover rate of Beal Lake, or the long distance water has to travel out of Beal Lake (Beal Lake → outlet canal → mainstem). None of the other backwaters have such extensive water delivery systems as Beal Lake.

The major finding of this study was the detection of lower water concentrations of selenium than those reported in most other studies (Lusk 1993; Radtke et al. 1988). Our greatest selenium concentration in water was 0.6 ppb total selenium at Beal Lake in 2004, Office Cove in 2004, and the DU Ponds in 2001. Lusk (1993) summarized selenium water concentrations and found concentrations ranged from 2.33-3.33 ppb in the mainstem of the lower Colorado River. Radtke et al.

(1988) reported dissolved selenium concentrations ranging from <1 to 2 ppb in both backwaters and the mainstem lower Colorado River. While Welsh (1992) found total selenium concentrations of 0.3 ppb - 0.8 ppb at Cibola NWR, most of the concentrations he reported ranged from 1.0-3.0 ppb. Sampling sites from this study ranged from backwaters to a few mainstem locations. Therefore, our concentrations, ranging from <0.3-0.6 ppb, were among the lowest ever reported in backwaters and the mainstem of the lower Colorado River.

We could not distinguish patterns between invertebrate samples at different backwaters because only one composite invertebrate sample was collected at each backwater in 2001 and 2004. To conduct statistical analysis, we had to pool invertebrate samples across backwaters to distinguish differences between years. Invertebrates were present in the backwaters their entire lifetime prior to sampling whereas crayfish were only exposed to backwaters for one month. Therefore, we expected invertebrate selenium concentrations to be greater in the invertebrates. The mean selenium invertebrate concentration in 2001 was 2.5 ± 1.42 ppm. An invertebrate sample from Beal Lake in 2001 had a selenium concentration of 4.4 ppm, which is above the threshold for a moderate selenium hazard (Lemly 1995). However, the 2004 macroinvertebrate concentration at Beal Lake was below this threshold.

Unfortunately, none of the fish samples collected have direct relevance to this study. Either we were unable to get late post-manipulation samples of whole-body razorbacks to evaluate if selenium bioaccumulation had occurred or the collected fish samples did have selenium bioaccumulation, but were not from treatment backwaters. We did compare selenium concentrations in whole body razorback suckers to assess differences in selenium concentrations after being held in the hatchery. Selenium concentrations increased in razorback sucker fingerlings stocked at Beal Lake in 2001 and at the DU Ponds in 2004 (Table 12). Given that all the fingerlings were raised from fry at the Willow Beach National Fish Hatchery, monitoring fingerling whole body selenium concentrations at the hatchery would be an easy way to track changes in selenium. Another useful monitoring strategy would be to monitor mature females and concentrations of selenium in their eggs to see if reproductive impairment has occurred.

While these concentrations reflect hatchery conditions, we wanted to present all the data we collected. Metal variations could result from a combination of oral exposure to both mainstem river water and food fed to the fish while in the hatchery. The arsenic mean in 2002 was higher than the NCBP 85th percentile (Schmitt and Brumbaugh 1990). We used the NCBP 85th percentile as an indicator of possible effects because an 85th percentile was calculated for most metals after extensive sampling across the conterminous United States (Hamilton et al. 2000a; Schmitt and Brumbaugh 1990). While fishes collected in the NCBP study were full-grown adult fishes, our razorback sucker whole body samples may not be considered adults. Razorback suckers are not considered adult until they are age 4+ and > 400 mm total length (USFWS 2004). Three razorback suckers had arsenic concentrations ranging from 2.1-2.8 ppm dry weight, which is slightly elevated over the 2 ppm dry weight threshold level at which arsenic concentrations could harm fish (Walsh et al. 1977). Six razorback suckers had copper concentrations that met or exceeded the NCBP 85th percentile samples in 2001. Eight razorback suckers in 2002 and 2004 had zinc concentrations greater than the NCBP 85th percentile. Therefore, arsenic is a contaminant of concern in backwaters along the lower Colorado River and copper and zinc remain contaminants of potential concern. While the NCBP 85th

percentile for selenium and selenium reproductive thresholds were developed for mature fishes, three razorback suckers had selenium concentrations above the NCBP 85th percentile and the 3-6 ppm dry weight threshold effects in warm water fishes (Bennett 1998), and one out of the three samples met the 4 ppm dry weight threshold for reproductive failure in fishes or juvenile mortality (Lemly 1996). These same 2004 fishes with moderate whole body selenium concentrations had concentrations similar to those reported by Radtke et al. (1988) in the mainstem of the river below the Palo Verde Outfall Drain on Cibola NWR. Other selenium concentrations in the Radtke et al. (1988) study were higher than those detected in our study (4.8-8.0 ppm dry weight at Havasu NWR (mainstem) and 5.2-5.6 ppm dry weight at Imperial NWR (Cibola Lake)).

Although we did not study West Meander comprehensively, selenium in one sample of mosquitofishes at 6.1 ppm dry weight was greater than the NCBP 85th percentile (2.92 ppm), the 4 ppm threshold in whole body fish recommended by Lemly (1996; Hamilton 2002), and the 6 ppm toxicity threshold for warmwater fishes (Bennett 1998). West Meander is flooded with Colorado River water every fall for five months to provide wintering waterfowl and wading bird habitat. It may act as a connected backwater during this period and, therefore, is prone to the same selenium bioaccumulation as the other backwaters.

Muscle plug data that could have been useful in detecting selenium bioaccumulation did not yield any results. None of the razorback sucker muscle plugs had metal concentrations greater than 3.4 ppm found in a razorback sucker muscle plug from the upper basin of the Colorado River (Waddell and May 1995). However, this could be due to sampling error (not enough mass for analysis) or analytical error (we did not specify to analyze for selenium only).

We also did not have thorough data on Lake Havasu, but bonytails in Lake Havasu had copper and selenium concentrations greater than the NCBP 85th percentile (4 and 2.92 ppm, respectively). Selenium at 3 ppm dry weight in one bonytail is at the bottom of the range for concern for warmwater fishes (Bennett 1998) and is below the threshold for reproductive effects in whole body fish (4 ppm; Lemly 1996). Although selenium tissue concentrations were not consistent, selenium remains a contaminant of concern at West Meander and in Lake Havasu. Continued monitoring of selenium in the lower Colorado River is especially important because selenium may be partially responsible for reproductive problems in razorback suckers (Waddell and May 1995).

<u>Other Metals</u>

No patterns were evident in other metals analyzed in this study. No metal concentrations in water exceeded Arizona Water Quality Standards. Arsenic, boron, and magnesium in water were significantly greater in 2004 than in 2001 at Beal Lake, Office Cove (As, B), and High Levee Pond (B, Mg), and the DU Ponds (As, B). Barium was significantly greater in 2001 water samples than in 2004 at Office Cove, High Levee Pond, and the DU Ponds. While differences in metal concentrations in water could be due to water, sediment, or sediment/water interactions, differences in metal concentrations in sediment are more likely a function of the original bedrock (Foth 1990). Variation in sediment concentrations at Office Cove, which had greater concentrations of iron, magnesium, and manganese than any of the other backwaters, could be due to enriched source material for the backwater. Office Cove was made with soils excavated for Central Arizona Project

(CAP) pumping plant construction. Bedrock in this area is composed of basaltic formations which naturally have elevated concentrations of iron and magnesium. Manganese is commonly associated with iron in these formations. Iron and magnesium also are present in the desert varnish on the rock faces and contribute to the red coloration of the rock in the area. Crushed rock from CAP construction mixed with surface water could leach iron, magnesium, and manganese into Office Cove (Doyle Wilson, pers. comm.). Water in Office Cove does not flow through; it is a closed system, where water can only come and go through one coarse-sediment berm. Any elements enriched in Office Cove when it was constructed will likely remain given its design.

We observed another interesting difference in the sediment data, where lead concentrations were statistically lower at all four backwaters in 2004 than in 2001. Again, given that the backwaters are all configured differently, we cannot explain this difference.

There were no differences in metal concentrations between the invertebrates and crayfish that were consistent over time and between metals. Invertebrate collections were made from populations present in the backwaters at the time of sampling. Crayfish were exposed to backwater conditions in situ for one month and were originally collected from the Bill Williams River. The metal concentrations in crayfish reflected one month of exposure, after a depuration period in laboratory water with no food. It is likely that some metals reached equilibrium in the crayfish. Indeed, arsenic, boron, and selenium likely did not reach equilibrium in crayfish tissue because their concentrations were consistently lower in crayfish than in the invertebrate samples. Selenium concentrations may not have been far from equilibrium because our concentrations were similar to other crayfish studies (Ruiz 1993; Welsh 1992; Prieto 1998). Metals such as barium, copper, and zinc had metal concentrations greater in the crayfish than in the invertebrate samples. It is possible that: 1) crayfish preferentially accumulate these metals over other metals since crayfish hemolymph contains hemocyanin, the copper-bearing protein which transports oxygen (Eisler 1998; Neff and Anderson 1977); 2) crayfish were near metal equilibrium in their tissues; or 3) differences in crayfish and invertebrate feeding strategies resulted in preferential uptake of different metals.

Hamilton et al. (2000b) found 4-6 ppm copper in their control bonytails which they reported was equal to or higher than levels in control fish from other studies. One of our bonytails had a similar copper concentration, 4.8 ppm, but the other bonytail had a copper concentration of 304 ppm, which is at least 50 times greater than concentrations expected in control fish. It is also 76-times the NCBP 85^{th} percentile of 4 ppm copper and greater than any of the maximum concentrations detected in the NCBP study (maximum copper = 154.8 ppm dry weight; Schmitt and Brumbaugh 1990). Eisler (1998) reported that copper accumulation in fish tissues was dependent on several different variables, including stress, diet and feeding state, and water quality parameters, but was not a good indicator of exposure to dietary or waterborne copper.

Mercury also was found in one fish at a high concentration (1 ppm). In fishes, methylmercury bioaccumulates faster and more efficiently than inorganic mercury and it is eliminated very slowly (US EPA 2001; Wiener and Spry 1996). It is standard to use EPA's fish tissue criterion for methylmercury (0.3 ppm) because nearly all of the mercury found in fishes is methylmercury (US EPA 2001). Wiener and Spry (1996) stated that 3 ppm wet weight (roughly equivalent to 12 ppm dry weight, assuming 75% moisture content) was equivalent to a no-observed-effect-concentration in brook trout. Our concentration in bonytail is much lower than this; however, concentrations protective of fish-eating birds begin at 3 ppm dry weight, which is the concentration at which birds begin to exhibit impaired reproduction (Thompson 1996).

Mosquitofish arsenic and zinc concentrations were greater than the NCBP 85^{th} percentile. The mosquitofish arsenic concentration was not greater than 5.4 ppm dry weight, so effects due to this concentration are unlikely (NRCC 1978). Eisler (1988) reported that arsenic in seafood in China is limited to 6-10 ppm fresh weight arsenic (roughly 24-40 ppm dry weight) before it is banned from human consumption. Our arsenic concentrations in mosquitofish were much lower than this recommended advisory. There are no zinc thresholds for fish tissue concentrations for acute or chronic toxicity or human consumption advisories. Therefore, zinc is a contaminant of potential concern at West Meander and copper is a contaminant of concern at Lake Havasu.

Water Quality

Water quality varied at each backwater, depending on the time of day and the characteristics of the backwater (Appendix 1). High Levee Pond had the best water quality, as indicated by low specific conductivity and Office Cove had the worst, as indicated by high specific conductivity. Water pH was generally alkaline; pH was consistently higher at Office Cove (pH = 8.1-9.27). Temperatures fluctuated according the time of day sampling occurred. Seasonal warming of the backwaters can be seen in the data. Dissolved oxygen was consistently high at Office Cove and High Levee Pond. We expected to see such high DO values at High Levee Pond since it is such a productive pond and the water flow through is highest among all of the backwaters in this study. Office Cove had a wind-blown aerator that could account for some of the high DO readings. Lack of mixing could also account for the low DO values seen at depth in Office Cove.

Previous Biological Data

Selenium on the lower Colorado River has been extensively studied in the past. Water concentrations of selenium appeared to be declining from reported concentrations in previous studies. The maximum selenium concentration in water in this study was 0.6 ppb. Welsh (1992) detected selenium in water as low as 0.3 ppb at Pretty Water but he measured backwater selenium concentrations from <0.4-5.0 ppb. Lusk (1993) reported selenium concentrations in the river as high as 2.33-3.31 ppb; however, these were data from the mainstem of the Colorado River.

Although previous studies did not examine the same backwaters we used in this investigation, crayfish and fishes were sampled in other seepage lakes and backwaters. For example, King et al. (2000) found that selenium concentrations in crayfish in his study (4.21 – 15.5 ppm dry weight) were consistent with those found at Imperial NWR (Lusk 1993), but were two- to three-times higher than those previously reported by others (Kepner unpub. data, Rusk 1991, Welsh and Maughan 1993, and Prieto 1998). All of the data from previous studies were collected from connected backwaters or from seepage lakes receiving groundwater inputs. The exception is King et al. (2000) where some of the data were from the mainstem of the Colorado River or from the Salton Sea. Our crayfish *in-situ* exposures probably did not reach selenium equilibrium in tissues because selenium concentrations in crayfish in this study were slightly lower than in many others. Our highest selenium concentration in crayfish, 2 ppm at the DU Ponds, was lower than the means from Rusk (1991) 2.24 ppm and Prieto (1998) 2.73 ppm.

Lusk (1993) also collected mosquitofish at Imperial NWR's backwaters and seepage lakes and found selenium concentrations ranging from 1.6 – 13.0 ppm dry weight. Lusk (1993) found greater geometric mean selenium concentrations in mosquitofish from backwaters (10.1 ppm) than from seepage lakes (3.81 ppm). Fish from Topock Marsh at Havasu NWR had selenium concentrations ranging from 4.3 – 17.9 ppm dry weight (King et al. 1993). Channel catfish, common carp, and largemouth bass collected from Topock Gorge and Topock Marsh at Havasu NWR had selenium concentrations ranging from 2.98 – 10.7 ppm dry weight (Andrews et al. 1997). Red shiner, threadfin shad, and largemouth bass collected in Topock Marsh had selenium concentrations ranging from 3.89 to 7.93 ppm dry weight (King et al. 2003). Fish from this study had selenium concentrations ranging from 0.93 – 6.1 ppm dry weight. Most of our fish did not have selenium concentrations comparable to these other studies because they had not been in backwaters (i.e. our razorback sucker data were from pre-stocking collections). Mosquitofish were the only fish collected from a backwater and they had the highest selenium concentration in this study. Selenium accumulation occurred in lower Colorado River backwaters (mosquitofish at West Meander) and was documented in a few fish samples from the river (bonytails).

SUMMARY

We conducted early pre-manipulation sampling of subject backwaters in 2001 and late post-manipulation sampling of converted backwaters in 2004. Management of Beal Lake and the DU Ponds continue to change as non-native fishes colonize the backwater, temperature and oxygen levels continue to fluctuate, and piscivorous birds prey on stocked native fish. Water management at the DU Ponds also continues to change, with water managers now relying solely on groundwater as opposed to the river water that was used during the beginning of our investigation. While there were some significant differences between metal concentrations over time, the only pattern that emerged was at Beal Lake. Concentrations of selenium in water, sediment, and crayfish were consistently high at Beal Lake. We also question why Beal Lake, as a pseudo-seep, had greater selenium concentrations than High Levee Pond, a connected lake. Prieto (1998) predicted that connected lakes would have greater selenium accumulation than pseudo-seeps. We believe that continued monitoring is warranted at Beal Lake.

Although selenium concentrations in water have declined over time, selenium bioaccumulation in crayfish and fishes still occurred. We did find greater selenium concentrations in crayfish from Beal Lake and the DU Ponds in 2001. This could be an indicator that these backwaters functioned as selenium sinks. We cannot be certain if this is related to our classification of Beal Lake as a pseudo-seep. However, little selenium was detected in the four 2004 invertebrate samples other than in the 19 crayfish samples. This could indicate no selenium build-up in the backwaters as predicted, but since the study design was not very robust, we caution against making any firm conclusions. Selenium increased in fingerling razorback suckers over three years from the Willow Beach National

Fish Hatchery although the increase was still below toxicity threshold levels in fish. It is possible that this could be related to the feed supplied to the larvae; if not, continued monitoring is warranted.

Selenium tissue concentrations between mosquitofish, razorback sucker muscle plugs, and bonytails were not consistent, but selenium remains a contaminant of concern at West Meander and in Lake Havasu. Differences in collections sites, length of exposure time, and types of fish and tissues collected could have contributed to this inconsistency. Although elevated at Beal Lake and the DU Ponds, selenium concentrations in crayfish in this study were lower than in crayfish from previous field studies. We found selenium elevated above thresholds in one out of three wild fish samples in this study; higher selenium accumulation occurred in a lower Colorado River occurred in a backwater (West Meander). We also found that zinc is a contaminant of potential concern at West Meander and copper is a contaminant of concern at Lake Havasu because of an elevated concentration in Lake Havasu.

MANAGEMENT ACTIONS

Documenting relative rates of selenium bioaccumulation in previously selenium-low environments will influence future management actions. If selenium loading occurs as a result of converting backwaters from true seeps to connected lakes and pseudo-seeps, then alternative management strategies should be considered in future design and implementation. Early and late post-manipulation comparisons were made, but we caution against drawing conclusions from them. Converting backwaters should be done cautiously while sites for this study continue to be manipulated and monitored. However, future actions on backwaters along the lower Colorado River should continue to monitor selenium concentrations pre- and post-manipulation. For instance, if managers continue to use Colorado River water at Beal Lake, crayfish and fish eggs should be monitored at these sites. Managers should sample crayfish and look for elevated selenium concentrations >4-5 ppm dry weight (Lemly 1995). Eggs from mature razorback suckers should also be sampled; look for exceedances above the 10-20 ppm dry weight threshold (Ohlendorf 2003; Lemly 1996). Sampling selenium in eggs is recommended, as selenium in eggs has been directly related to decreased reproductive performance in other studies (Baumann and Gillespie 1986; Gillespie and Bauman 1986). Studies at Beal Lake also need to focus on how selenium dynamics are affected by the size of the water body, the length of its water delivery canals, and its function as a pseudo-seep. It may be important to characterize berm flow rates and permeability. These indices will help us understand backwater residence times and further delineate the difference between pseudo-seeps and true seeps. Also, if West Meander continues to be managed in the same way, selenium tissue monitoring should occur there at frequent intervals.

Although selenium concentrations from fingerlings from Willow Beach National Fish Hatchery were below threshold effects levels, there was a significant selenium increase in fingerlings from 2001 to 2004. We recommend selenium monitoring of fishes at Willow Beach because selenium bioaccumulation is documented in the Colorado River and the Colorado River is the source of hatchery water for the Willow Beach National Fish Hatchery. The hatchery should monitor razorback sucker eggs for exceedances above 10-20 ppm selenium (Ohlendorf 2003; Lemly 1996).

This study will serve as a useful tool for the pre-manipulation monitoring and should be used for comparison with post-manipulation results. High Levee Pond was an appropriate reference in this study and should continue to be used as a model backwater since selenium concentrations did not change over time. High Levee Pond also had one of the lowest crayfish selenium concentrations in this study and as compared to other studies. This also indicates that a flow-through backwater like High Levee Pond may provide optimal fishery conditions while keeping selenium bioaccumulation at bay (Hamilton et al. 2004).

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Appendix 1. A summary of field measurements of water quality at lower Colorado River backwaters, 2004. There is variation within each water quality parameter because the data for each depth were compiled from up to six different sampling locations within the backwater.

LOCATION	**DATE**	**TIME**	**DEPTH m**	**TEMP °C**	**DO mg/L**	**SC uS/cm**	**pH**
Beal Lake	6/21/2004	0730-0900	0	27.03 – 29.16	4.59 – 8.02	1510 – 3190	8.04 – 8.59
			0.5	27.05 – 29.14	3.96 – 7.57	1610 – 3190	8.02 – 8.56
			1.0	27.31 – 28.91	1.17 – 7.28	2040 – 3210	7.93 – 8.56
			1.5	27.16 – 28.82	0.72 – 6.93	2030 – 3240	7.93 – 8.55
			2.0	27.35 – 28.53	2.8 – 7.32	2940 – 3280	8.12 – 8.53
	9/23/2004	1330-1430	0	20.71 – 22.58	7.32 – 9.45	2060 – 3880	7.97 – 8.36
			1.0	20.1 – 22.38	6.39 – 9.05	2170 – 3930	8.04 – 8.34
			1.5	20.65 – 20.78	6.29 – 6.55	3830 – 3880	8.07 – 8.24
			2.0	19.39 – 19.96	5.84 – 6.66	3680 – 3780	8.28 – 8.33
Office Cove^	3/10/2004	1000	0	25.27 – 25.99	8.96 – 9.13	2970 – 2980	8.19 – 8.41
			0.5	22.83 – 25.84	8.58 – 10.22	2980 – 3030	8.34 – 8.44
			1.0	21.8 – 22.19	8.8 – 9.35	2950 – 3010	8.36 – 8.45
			1.5	19.77 – 21.06	4.41 – 6.55	2990 – 2990	8.29 – 8.35
			2.0 (1)	17.33	1.01	2980	8.18
			2.5 (1)	16.31	0.42	2970	8.13
			3.0 (1)	15.82	0.29	2940	8.10
	6/8/2004	0800	0	27.76 - 27.83	8.7 – 9.10	3080 – 3090	9.13 – 9.23
			0.5	27.72 – 27.79	8.4 – 8.8	3060 – 3080	9.17 – 9.22
			1.0	27.7 – 27.74	7.97 – 8.25	3050 – 3070	9.19 – 9.22
			1.5	27.47 – 27.66	6.8 – 8.14	3070 – 3100	9.18 – 9.2
			2.0	27.01 – 27.37	4.83 – 5.57	3007 – 3090	9.14 – 9.19
			2.5	26.4 – 26.82	0.52 – 5.97	3050 – 309	9.06 – 9.18
			3.0 (1)	25.12	0.41	3020	8.91
			3.4 (1)	23.71	1.08	3000	8.78
	9/23/2004	0800-0830	0	24.21 – 24.23	0.57 - 0.98	2210 – 3220	9.13 – 9.25
			1.0	24.21 – 24.23	0.35 – 0.46	3200 – 3240	9.23 – 9.27
			1.6 (1)	24.19	0.47	3210	9.27
			2.0	24.23-24.23	0.27-0.37	3200-3210	9.23-9.26
			3.0 (1)	24.14	0.29	3200	9.27
			3.8 (1)	24.14	0.22	3190	9.27
High Levee Pond	3/10/2004	1220	0.0	20.1	8.1	1066	7.4
			0.5	20	7.8	1076	7.4
			1	19.9	7.7	1059	7.4
			1.5	19.7	7.3	1061	7.4
			2	19.6	7	1061	7.4
			2.5	19.5	6.7	1065	7.4
			2.9	19.4	5.8	1063	7.4
	6/23/2004	0650	0	27.1	10.6	980	7.3
			0.5	27.2	10.8	980	7.4
			1	27.2	10.8	979	7.5
			1.5	27.2	10.8	979	7.6
			2	27.1	10.6	980	7.6
			2.5	26.9	9.2	978	7.7
			3	26.6	3.2	935	7.7
	9/23/2004	UN	0	22.45-22.89	8.5-9.7	1400-1440	8.8-9.1‡
			0.5	22.23-22.84	8.9-9.9	1430-1440	7-9.2
			1	22.44-22.61	9.2-10.4	1430-1440	7-9.3
			1.5	22.69	9	1430	8.9

LOCATION	DATE	TIME	DEPTH m	TEMP °C	DO mg/L	SC uS/cm	pH
DU Ponds	6/28/2004	1930-2000	0	25.46 – 29.3	0.28 – 9.8	2090 – 2640	6.83 – 8.54
	Only pond 1		0.5	28.93 – 29.3	7.43 – 10.3	2080 – 2130	8.5 – 8.83
			1	28.96 – 29.2	8.9 – 11.05	2060 – 2180	0.4 – 8.83
			1.5	28.41 – 28.97	2.78 – 10.95†	2070 – 2320	7.69 – 8.82
			2.0 (1)	28.85	5.92	2150	6.86
	6/29/2004	0515-0530	0	27.17 – 27.63	5.59 – 7.2	2080 – 2220	8.06 – 8.56
	Only pond 1		0.5	27.21 – 27.65	5.84 – 7.49	2090 – 2210	8.06 – 8.58
			1	27.18 – 27.64	5.54 – 7.43	2090 – 2210	8.07 – 8.57
			1.5	27.39 – 27.92	1.7 – 5.48	2090 – 2360	6.93 – 8.24
			2.0 (1)	25.35	0.44	2640	6.87
	9/13/2004	0700-0730	0	28.4 – 28.57	1.01 – 3.41	1460 – 3310	7.66 – 7.83
	Ponds 1 and 2		0.5	28.4 – 28.6	0.03 – 3.29	1470 – 3340	7.66 – 7.82
			1	28.4 – 28.6	0.24 – 3.04	1470 – 3350	7.65 – 7.82
			1.5	27.66 – 28.43	0.17 – 3.15	1420 – 3580	7.58 – 7.8
			2.0 (1)	25.7	4.55*	1370	7.70
			2.5 (1)	25.4	5.08	1360	7.7
		1700-1845	0	29.99 – 31.33	2.44 – 6.63	1490 – 3380	7.66 – 7.88
			0.5	29.81 – 30.77	0.72 – 4.75	1480 – 3320	7.6 – 7.77
			1	28.55 – 29.57	0.31 – 3.88	1480 – 3890	7.49 – 7.69
			1.5	28.21 – 28.94	0.18 – 5.26	1480 – 3620	7.48 – 7.69
			2.0 (1)	26.87	6.4	1400	7.63

(n) = number of samples, if less than two.
^Office Cove water quality parameters really highlight the lack of DO there and the problems with a consistently high pH. This environment was definitely not hospitable to fishes.
‡ High Levee Pond pH data increased dramatically in September 2004. The cause of this pH change is unknown. This could definitely be a stressor to fish in the backwater.
†Variation like this might suggest equipment issues, but it is also likely that data were collected near shore, in vegetation, or in otherwise less desirable habitats that contributed to the variation in data.
*The bottom of the DU Ponds is oxygenated and the top is not because by 2004, groundwater was being pumped in from the bottom overnight to increase DO concentrations in the water column.

Appendix 2. All data from 2001with detection limits listed when a sample was not detected (<DL).

dry weight, ppm		% Moisture	Al	As	B	Ba	Be	Cd	Cr	Cu	Fe	Hg
BLSED1	sediment	48.5	14000	4.3	10	184	0.64	0.5	16	11	12700	<.100
BLSED2	sediment	65.8	15400	6.7	10	229	0.73	0.4	17	16	15200	<.100
BLSED3	sediment	63.8	2280	3.8	<10.0	130	<.200	0.4	3.3	3.8	4450	<.100
BLSED4	sediment	43.4	2910	3.4	<10.0	156	<.200	0.4	3.8	3.2	4950	<.100
BLSED5	sediment	34.1	7140	11	<10.0	214	0.4	0.4	9.2	9	17300	<.100
BLSED6	sediment	61.5	8920	7.5	<10.0	186	0.5	0.5	11	12	13800	<.100
BWSED1	sediment	59.3	18100	11	<10.0	709	1.1	0.5	22	26	27900	<.100
BWSED2	sediment	49.2	16300	11	<10.0	912	0.88	0.66	21	22	24900	<.100
BWSED3	sediment	58.2	37300	16	30	495	1.9	0.4	44	64	38100	<.100
BWSED4	sediment	71.1	33200	16	20	442	1.8	0.5	38	52	36100	<.100
BWSED5	sediment	60.5	21900	15	10	488	1.2	0.5	31	35	31100	<.100
BWSED6	sediment	71.7	26700	25	<10.0	399	1.8	0.5	31	37	40100	0.1
DU201	sediment	30.3	5570	2.2	<10.0	122	0.2	0.3	6.7	4.2	6380	<.100
DU202	sediment	31.7	2830	2	<10.0	104	<.200	0.3	3.8	2	4180	<.100
DU203	sediment	22.4	2720	1.6	<10.0	156	<.200	0.2	5	<1.00	4750	<.100
DU204	sediment	29.2	2700	1	<10.0	102	<.200	<.200	4.1	1	3900	<.100
DU205	sediment	28.2	8710	4.2	<10.0	175	0.4	0.3	9.9	8.6	10100	<.100
DU206	sediment	31.3	5790	2.7	<10.0	162	0.3	0.4	7.2	5.1	7290	<.100
HLPSED1	sediment	84.4	9410	5.9	10	199	0.5	<.200	11	11	12900	<.100
HLPSED2	sediment	68.6	8880	3.9	10	117	0.4	<.200	11	7	9310	<.100
HLPSED3	sediment	63	9720	4.4	10	134	0.4	0.2	11	6.5	10800	<.100
HLPSED4	sediment	73.8	9210	4.4	<10.0	153	0.5	0.4	10	10	11300	<.100
HLPSED5	sediment	59.2	11400	4.5	<10.0	171	0.5	<.200	13	6.8	10500	<.100
HLPSED6	sediment	56	7650	5.4	10	166	0.4	<.200	10	7	8220	<.100
BWINV1	invertebrate	74.9	809	1.6	38	42.2	<.100	0.2	0.9	12	1140	<.100
DUINV1	invertebrate	71.7	796	2.1	3	113	<.100	<.100	0.6	24	780	<.100
HAVINV1	invertebrate	69	2260	5	4	112	0.1	0.53	2.4	25	2440	<.100
HLPINV1	invertebrate	82.2	873	4.4	4	33.4	<.100	0.1	1	15	887	<.100
CIBFISH1	fish	68.3	130	1.2	<2.00	20	<.100	<.100	6	3.3	190	<.100
RZB1	fish	75.2	51	2.8	<2.00	3.4	<.100	0.1	1.6	4.3	210	<.100
RZB10	fish	67.8	91	2.1	<2.00	3.9	<.100	<.100	1	4	258	0.1
RZB11	fish	67.1	69	1.1	<2.00	2.6	<.100	<.100	1	3.6	140	0.1
RZB2	fish	70.7	37	1.4	<2.00	3.5	<.100	0.1	1	5.5	160	<.100
RZB3	fish	71.4	40	1.4	<2.00	2.5	<.100	<.100	2.3	3.6	140	<.100
RZB4	fish	70.9	110	1.3	<2.00	2	<.100	<.100	1	3.4	98	<.100
RZB5	fish	71.8	59	2	<2.00	4.6	<.100	<.100	2.6	3.2	213	0.1

Appendix 2 continued.

dry weight, ppm		% Moisture	Al	As	B	Ba	Be	Cd	Cr	Cu	Fe	Hg
RZB6	fish	71.6	40	1.9	<2.00	3.8	<.100	<.100	1.6	4	160	<.100
RZB7	fish	73.1	120	2.1	2	5.6	<.100	<.100	3.3	4	423	0.1
RZB8	fish	72.3	61	2	<2.00	4.2	<.100	<.100	1.6	4.3	240	0.1
RZB9	fish	70.1	21	1.4	<2.00	2.4	<.100	<.100	<.500	3.4	100	<.100
BWCRAY1	crayfish	75.1	476	2.6	9.5	489	<.100	0.2	<.500	110	663	<.100
BWCRAY2	crayfish	77.3	369	1.6	9.3	318	<.100	0.41	0.6	213	452	<.100
BWCRAY3	crayfish	87.6	150	1.4	8.7	434	<.100	0.42	<.500	142	221	<.100
BWCRAY4	crayfish	73.3	249	1.3	9.5	432	<.100	0.2	<.500	142	317	<.100
BWCRAY5	crayfish	68.5	440	1.3	8.5	488	<.100	0.34	<.500	130	448	<.100
BWREF1	crayfish	55.8	308	1.7	5	386	<.100	0.2	<.500	122	386	<.100
BWREF2	crayfish	59.8	1330	3.1	6.5	1190	<.100	<.100	1	75.2	1400	<.100
CRYHAV01	crayfish	81	1400	2.8	5	508	<.100	0.36	2.7	164	955	<.100
CRYHAV04	crayfish	74.2	376	2.3	5	504	<.100	0.5	0.8	146	461	<.100
CRYHAV05	crayfish	76.7	338	2.4	5	399	<.100	0.2	1	133	430	0.1
CRYHAV06	crayfish	77.1	229	2.5	4	457	<.100	0.31	<.500	160	213	<.100
DU2CRY2	crayfish	81.5	140	1.7	4	368	<.100	0.32	<.500	87.8	190	<.100
DU2CRY3	crayfish	89.7	289	1.7	4	212	<.100	0.2	0.7	62.4	392	<.100
DU2CRY4	crayfish	86.7	160	2.1	5	353	<.100	0.2	<.500	119	258	<.100
DU2CRY6	crayfish	88.3	234	3.4	6.4	566	<.100	0.1	0.7	137	476	0.2
HLPCRY1	crayfish	72.2	140	1.6	5	381	<.100	0.3	<.500	111	268	<.100
HLPCRY2	crayfish	84.9	140	1.8	4	498	<.100	0.2	<.500	74.4	190	<.100
HLPCRY3	crayfish	83.5	291	1.8	4	397	<.100	0.31	0.6	152	474	<.100
HLPCRY4	crayfish	85.5	110	1.2	3	308	<.100	0.2	2	45.5	215	<.100
HLPCRY5	crayfish	87.1	190	1.5	3	429	<.100	0.2	0.6	107	281	<.100
HLPCRY6	crayfish	83.4	331	2	4	411	<.100	0.2	1	117	474	<.100

Appendix 2 continued.

dry weight, ppm		Mg	Mn	Mo	Ni	Pb	Se	Sr	V	Zn
BLSED1	sediment	11100	326	<5.00	10	35	1	154	28	55
BLSED2	sediment	12200	373	<5.00	10	45	2.8	295	34	66
BLSED3	sediment	4510	170	<5.00	<5.00	25	1	177	7	19
BLSED4	sediment	4860	200	<5.00	<5.00	22	<.500	91	7.5	21
BLSED5	sediment	10300	396	<5.00	9	38	0.6	129	18	54
BLSED6	sediment	9940	346	<5.00	10	41	2.5	233	21	59
BWSED1	sediment	14600	1200	<5.00	24	41	0.8	481	43	110
BWSED2	sediment	13300	747	<5.00	25	37	0.8	363	38	97
BWSED3	sediment	17800	1110	<5.00	42	46	1	367	63	140
BWSED4	sediment	17400	1590	5	37	47	2	585	62	120
BWSED5	sediment	13900	1150	<5.00	29	38	0.8	378	52	110
BWSED6	sediment	15900	1690	<5.00	26	43	0.9	476	61	130
DU201	sediment	6180	208	<5.00	5	20	<.500	111	12	22
DU202	sediment	4230	150	<5.00	<5.00	16	<.500	100	6.7	12
DU203	sediment	3630	130	<5.00	<5.00	10	<.500	60	10	11
DU204	sediment	3470	130	<5.00	<5.00	10	<.500	82	7.7	12
DU205	sediment	8700	260	<5.00	9	27	0.5	138	18	39
DU206	sediment	7070	224	<5.00	6	23	<.500	120	13	25
HLPSED1	sediment	9360	439	<5.00	9	34	2	673	23	41
HLPSED2	sediment	6890	300	<5.00	7	28	0.8	201	22	29
HLPSED3	sediment	6640	403	<5.00	7	28	1	314	22	32
HLPSED4	sediment	9520	357	<5.00	9	32	1	357	21	44
HLPSED5	sediment	8360	445	<5.00	7	29	0.7	352	23	34
HLPSED6	sediment	7570	280	<5.00	7	24	0.7	239	16	30
BWINV1	invertebrate	6400	127	<2.00	1	1.5	1	187	5.3	64.2
DUINV1	invertebrate	1770	113	<2.00	<.500	1.2	2.5	1220	1.9	36
HAVINV1	invertebrate	2370	83.3	<2.00	1.9	4.1	4.4	827	8.8	52.3
HLPINV1	invertebrate	1650	112	<2.00	0.8	1.2	2.1	199	2.9	86.4
CIBFISH1	fish	2230	28	<2.00	2.4	1.6	6.1	232	0.6	181
RZB1	fish	1370	165	<2.00	0.5	<.200	1.1	225	1.5	126
RZB10	fish	1170	45	<2.00	<.500	<.200	1.2	231	0.7	116
RZB11	fish	1020	15	<2.00	0.7	<.200	0.93	163	0.6	84.4
RZB2	fish	1240	21	<2.00	<.500	<.200	1	222	<.500	125
RZB3	fish	1320	31	<2.00	<.500	<.200	1.1	215	0.6	102
RZB4	fish	1120	23	<2.00	<.500	<.200	1.1	192	0.8	129
RZB5	fish	1220	41	<2.00	<.500	<.200	1.2	229	1	139

Appendix 2 continued.

dry weight, ppm		Mg	Mn	Mo	Ni	Pb	Se	Sr	V	Zn
RZB6	fish	1200	40	<2.00	<.500	<.200	1.2	205	0.9	122
RZB7	fish	1360	99.3	<2.00	<.500	0.2	1.5	266	1	118
RZB8	fish	1430	48	<2.00	<.500	<.200	1.3	286	0.9	141
RZB9	fish	1160	33	<2.00	<.500	<.200	1.1	209	<.500	97.2
BWCRAY1	crayfish	4350	917	<2.00	0.5	1.5	0.6	1430	1	78
BWCRAY2	crayfish	3560	333	<2.00	0.8	0.6	0.75	1070	1	105
BWCRAY3	crayfish	3650	454	<2.00	<.500	0.78	0.6	1240	<.500	96.1
BWCRAY4	crayfish	4000	212	<2.00	<.500	0.6	0.73	1720	0.6	79.8
BWCRAY5	crayfish	4390	406	<2.00	<.500	0.88	0.5	1350	1	87.9
BWREF1	crayfish	3970	201	<2.00	<.500	0.83	<.200	1160	1.8	95
BWREF2	crayfish	4450	525	<2.00	1	3.1	0.4	1470	3.3	149
CRYHAV01	crayfish	3680	389	<2.00	1	1.9	1.6	1360	3.8	85.4
CRYHAV04	crayfish	3750	416	<2.00	<.500	1.1	0.91	1430	1.6	78.1
CRYHAV05	crayfish	4630	171	<2.00	0.6	0.7	1.5	1330	1	87
CRYHAV06	crayfish	3720	306	<2.00	<.500	0.67	1.3	1410	1	87.6
DU2CRY2	crayfish	4720	323	<2.00	<.500	0.63	0.83	1300	0.6	76.5
DU2CRY3	crayfish	5070	113	<2.00	0.8	0.76	2	1360	1	149
DU2CRY4	crayfish	4610	257	<2.00	<.500	0.5	1.3	1390	0.7	76.5
DU2CRY6	crayfish	5140	174	<2.00	<.500	0.4	1.3	1380	0.7	80
HLPCRY1	crayfish	4080	268	<2.00	<.500	0.84	0.61	1190	1	84.2
HLPCRY2	crayfish	4310	360	<2.00	<.500	0.6	0.4	1400	0.7	58.7
HLPCRY3	crayfish	3660	581	<2.00	<.500	0.6	0.81	1030	1	92.1
HLPCRY4	crayfish	5880	162	<2.00	<.500	0.2	0.8	1110	0.5	68.1
HLPCRY5	crayfish	4180	237	<2.00	<.500	0.5	0.6	1260	0.9	64.5
HLPCRY6	crayfish	4330	230	<2.00	<.500	0.68	0.66	1240	1	87.2

Appendix 2 continued.

wet weight, ppm		Al	As	B	Ba	Be	Cd	Cr	Cu	Fe	Hg	Mg	Mn
BL1	Water	0.39	0.0026	0.13	0.114	<0.0005	0.001	<0.002	0.013	0.27	<.0005	24.6	0.022
BL2	Water	0.55	0.0026	0.13	0.129	<0.0005	0.001	<0.002	0.006	0.32	<.0005	26.1	0.028
BL3	Water	0.1	0.0017	0.15	0.134	<0.0005	0.001	<0.002	0.002	0.08	<.0005	33.6	0.011
BL4	Water	0.11	0.0025	0.24	0.153	<0.0005	0.001	<0.002	0.0075	0.1	<.0005	57.4	0.012
BL5	Water	0.12	0.0022	0.21	0.146	<0.0005	0.001	<0.002	0.004	0.08	<.0005	50.1	0.0079
BL6	Water	0.073	0.0026	0.21	0.167	<0.0005	0.001	<0.002	0.003	0.07	<.0005	51.4	0.005
DU201W	Water	1.4	0.0023	0.27	0.11	<0.0005	0.0007	<0.002	0.005	0.7	<.0005	44.6	0.034
DU202W	Water	0.82	0.0031	0.29	0.131	<0.0005	<0.0005	<0.002	0.004	0.68	<.0005	50.8	0.086
DU203W	Water	0.4	0.0031	0.27	0.123	<0.0005	0.001	<0.002	0.0062	0.35	<.0005	48.4	0.079
DU204W	Water	0.48	0.0043	0.4	0.173	<0.0005	0.001	<0.002	0.003	0.53	<.0005	67.5	0.13
DU205W	Water	0.28	0.0033	0.39	0.165	<0.0005	0.001	<0.002	<0.002	0.23	<.0005	67	0.07
DU206W	Water	0.37	0.0031	0.4	0.166	<0.0005	0.001	<0.002	0.003	0.3	<.0005	66.8	0.072
HLP07W	Water	0.075	0.0019	0.15	0.134	<0.0005	0.001	<0.002	<.002	0.06	<.0005	37.3	0.081
HLP08W	Water	0.05	0.002	0.17	0.138	<0.0005	0.001	<0.002	<.002	<.05	<.0005	39.4	0.073
HLP09W	Water	0.33	0.0018	0.18	0.139	<0.0005	0.001	<0.002	<.002	<.05	<.0005	39.4	0.08
HLP10W	Water	0.03	0.001	0.15	0.116	<0.0005	0.001	<0.002	<.002	<.05	<.0005	33.2	0.077
HLP11W	Water	0.03	0.0017	0.17	0.139	<0.0005	0.001	<0.002	<.002	<.05	<.0005	39.3	0.067
HLP12W	Water	0.2	0.001	0.12	0.102	<0.0005	0.001	<0.002	<.002	0.18	<.0005	29.1	0.07
OC13W	Water	0.29	0.0075	1.6	0.074	<0.0005	0.0005	<0.002	<.002	0.09	<.0005	30.1	0.041
OC14W	Water	0.24	0.007	1.5	0.072	<0.0005	0.0005	<0.002	<.002	0.06	<.0005	29.2	0.036
OC15W	Water	0.24	0.0076	1.6	0.074	<0.0005	0.001	<0.002	<.002	0.06	<.0005	29.8	0.036
OC16W	Water	0.22	0.0073	1.6	0.073	<0.0005	0.0005	<0.002	<.002	0.06	<.0005	29.5	0.036
OC17W	Water	0.25	0.0074	1.6	0.072	<0.0005	<0.0005	<0.002	<.002	<.05	<.0005	29.8	0.035
OC18W	Water	0.21	0.0071	1.5	0.069	<0.0005	0.0007	<0.002	<.002	0.05	<.0005	28.2	0.032

Appendix 2 continued.

wet weight, ppm		Mo	Ni	Pb	Se	Sr	V	Zn
BL1	Water	<.02	0.007	<0.005	0.0011	0.845	0.0046	0.32
BL2	Water	<.02	0.006	<0.005	0.001	0.884	0.0048	0.26
BL3	Water	<.02	0.007	<0.005	0.0003	1.1	0.001	0.24
BL4	Water	<.02	0.008	<0.005	0.0003	1.86	0.002	0.4
BL5	Water	<.02	<.005	<0.005	0.0004	1.57	0.002	0.3
BL6	Water	<.02	0.005	<0.005	0.0005	1.68	0.002	0.17
DU201W	Water	<.02	<0.005	<0.005	0.0005	1.54	0.0057	0.007
DU202W	Water	<.02	<0.005	<0.005	0.00074	1.58	0.0055	<0.005
DU203W	Water	<.02	<0.005	<0.005	0.00067	1.58	0.0042	<0.005
DU204W	Water	<.02	0.006	<0.005	0.0005	2.21	0.003	<0.005
DU205W	Water	<.02	<0.005	<0.005	0.0004	2.04	0.002	<0.005
DU206W	Water	<.02	<0.005	<0.005	0.0005	2.03	0.002	0.009
HLP07W	Water	<.02	<0.005	<0.005	<0.0002	1.21	0.003	0.009
HLP08W	Water	<.02	<0.005	<0.005	<0.0002	1.28	0.002	<0.005
HLP09W	Water	<.02	0.006	<0.005	<0.0002	1.28	0.001	<0.005
HLP10W	Water	<.02	<0.005	<0.005	0.0003	1.08	0.002	<0.005
HLP11W	Water	<.02	<0.005	<0.005	<0.0002	1.29	0.001	<0.005
HLP12W	Water	<.02	<0.005	<0.005	<0.0002	0.934	0.002	<0.005
OC13W	Water	0.04	0.005	<0.005	0.0004	0.699	0.006	0.01
OC14W	Water	0.04	0.005	<0.005	0.0003	0.682	0.0058	0.007
OC15W	Water	0.04	0.1	<0.005	0.0002	0.701	0.0061	<0.005
OC16W	Water	0.04	0.006	<0.005	0.0003	0.693	0.0056	0.005
OC17W	Water	0.04	<0.005	<0.005	0.0002	0.667	0.0057	<0.005
OC18W	Water	0.04	<0.005	<0.005	0.0003	0.664	0.0057	<0.005

Appendix 3. All data from 2004 with detection limits listed when a sample was not detected (<DL).

dry weight, ppm		% Moisture	Al	As	B	Ba	Be	Cd	Cr	Cu	Fe	Hg
BWRINV04	Invertebrate	90.3	6070	7.2	100	232	0.32	0.5	5.4	13	6970	<0.6
HAVINV04	Invertebrate	75.1	3670	5	22	151	0.2	0.7	3.3	8.5	4330	<1
HLPINV04	Invertebrate	73.9	2470	3.1	15	101	0.1	<0.1	2.9	20	3420	<0.1
MPRZB1	Muscle	54.8	93	<9	<9	3.9	<0.1	<0.6	113	2	1300	<2
MPRZB10	Muscle	67.6	32	<6	<6	2.8	<0.1	<0.4	2	0.8	39	<1
MPRZB11	Muscle	59.9	30	<4	<7	2	<0.1	<0.4	4.9	1	44	1
MPRZB12	Muscle	73.5	30	<6	<6	2.2	<0.1	0.5	2.9	1	160	<1
MPRZB2	Muscle	71.8	52	<6	<6	2.1	<0.1	0.4	54	2	1120	<1
MPRZB3	Muscle	60.5	40	<8	<8	3.1	<0.1	0.6	32	2	590	<2
MPRZB4	Muscle	71.5	52	<6	<6	2.1	<0.1	1.4	16	0.7	470	<1
MPRZB5	Muscle	67	42	<7	<7	3.1	<0.1	<0.4	1	0.7	66	<1
MPRZB6	Muscle	70.4	190	<9	<9	9	<0.1	0.5	82	3.7	1600	<2
MPRZB7	Muscle	33.3	100	<30	<30	19	<0.1	<2	5	<3	1600	<5
MPRZB8	Muscle	69.7	30	<5	<5	2.6	<0.1	0.4	3	0.8	83	<1
MPRZB9	Muscle	63.1	20	<6	<6	3.1	<0.1	0.6	2.1	1	42	<1
BLSED19 2	Sediments	59.8	12300	6.2	20	183	0.66	0.5	14	13	14100	<0.1
BLSED20 2	Sediments	74.8	9250	7.1	20	278	0.5	0.5	11	12	10600	<0.1
BLSED21 2	Sediments	83.1	5960	3.9	30	268	0.3	0.4	7.1	8.5	7030	<0.1
BLSED22 2	Sediments	88.9	8690	5.6	36	356	0.4	0.5	10	11	9950	<0.1
BLSED23 2	Sediments	59.7	6190	6.2	10	170	0.3	<0.2	6.2	6.7	8840	<0.1
BLSED24 2	Sediments	67.3	12200	7.3	20	216	0.6	0.6	14	14	14200	<0.1
DU2SED01 2	Sediments	49.7	6790	3.9	<10	131	0.4	<0.2	8.2	6.9	8600	<0.1
DU2SED02 2	Sediments	58.3	3230	3.5	10	140	0.2	0.3	4.4	6.1	6380	<0.1
DU2SED03 2	Sediments	58.4	5100	3.9	10	220	0.3	0.4	6.5	6	7920	<0.1
DU2SED04 2	Sediments	48.4	2700	1.9	10	184	<0.2	0.4	3.7	3	4410	<0.1
DU2SED05 2	Sediments	54.3	4000	3.1	<10	219	0.3	0.6	6	6	7570	<0.1
DU2SED06 2	Sediments	62.5	7510	3.7	20	305	0.4	<0.2	9.4	8	8780	<0.1
HLPSED13 2	Sediments	78.8	7660	4.7	20	145	0.4	0.4	13	8.3	11000	<0.1
HLPSED14 2	Sediments	82.6	7500	3.8	10	132	0.4	0.5	8.9	8.1	9120	<0.1
HLPSED15 2	Sediments	76.6	6620	2.9	10	154	0.4	0.4	7.5	7.2	8730	<0.1
HLPSED16 2	Sediments	82.8	10700	4.8	20	209	0.6	0.5	12	12	12400	<0.1
HLPSED17 2	Sediments	58.5	4300	3	<10	94.8	0.2	0.5	5.1	3.6	5590	<0.1
HLPSED18 2	Sediments	73.9	12200	6.7	20	275	0.6	0.5	14	12	12400	<0.1
OCSED07 2	Sediments	54.7	18200	6.3	20	662	1.1	0.5	20	21	28000	<0.1
OCSED08 2	Sediments	57	19800	7.8	20	818	1	0.5	24	22	27200	<0.1

Appendix 3 continued.

dry weight, ppm		% Moisture	Al	As	B	Ba	Be	Cd	Cr	Cu	Fe	Hg
OCSED09 2	Sediments	54	27900	9.3	20	573	1.6	0.5	27	33	35400	<0.1
OCSED10 2	Sediments	70.5	27700	15	30	534	1.5	0.74	28	31	34800	<0.1
OCSED11 2	Sediments	62.4	13600	21	10	304	1.2	0.2	16	23	30100	<0.1
OCSED12 2	Sediments	70.8	19600	14	20	480	1.2	0.5	24	29	30600	<0.1
BWRBTC1	Whole Body	68.3	59	0.93	<2	11	<0.1	<0.1	1	4.8	88	0.1
BWRBTC2	Whole Body	70.2	39	0.74	<2	9.8	<0.1	<0.1	1	304	85	0.2
RZBDU2-1	Whole Body	73	43	0.82	<2	0.4	<0.1	0.1	<0.5	3.2	56	<0.1
RZBDU2-10	Whole Body	72	30	0.78	<2	0.4	<0.1	<0.1	2	2.7	46	<0.1
RZBDU2-2	Whole Body	75	74	0.68	<2	0.68	<0.1	<0.1	<0.5	3.1	79	<0.1
RZBDU2-3	Whole Body	71.2	52	0.6	<2	0.5	<0.1	<0.1	5.6	2.9	87	<0.1
RZBDU2-4	Whole Body	72.4	11	0.7	<2	0.5	<0.1	<0.1	7.9	3.1	69	<0.1
RZBDU2-5	Whole Body	71.8	53	0.67	<2	0.3	<0.1	0.1	<0.5	3.3	50	<0.1
RZBDU2-6	Whole Body	71	74	0.71	<2	0.4	<0.1	<0.1	<0.5	2.8	53	<0.1
RZBDU2-7	Whole Body	72.8	41	0.79	<2	0.5	<0.1	<0.1	<0.5	4.3	46	<0.1
RZBDU2-8	Whole Body	69.8	43	0.79	<2	0.3	<0.1	<0.1	3.3	2.7	48	<0.1
RZBDU2-9	Whole Body	66.7	21	0.5	<2	0.2	<0.1	<0.1	<0.5	2.6	34	<0.1

Appendix 3 continued.

dry weight, ppm		Mg	Mn	Mo	Ni	Pb	Se	Sr	V	Zn
BWRINV04	Invertebrate	15500	445	3	5.1	7.5	<2	765	58	57.8
HAVINV04	Invertebrate	4860	258	3	1.8	6.3	<3	460	12	55.3
HLPINV04	Invertebrate	2750	296	<2	1.8	2.7	1	784	5.8	53.6
MPRZB1	Muscle	1160	14	<2	35	<4	<3	21.7	<2	157
MPRZB10	Muscle	820	2.9	<2	<0.7	<2	<2	53.5	1	128
MPRZB11	Muscle	600	0.7	<2	<0.9	<3	<2	2.3	2	118
MPRZB12	Muscle	994	5.9	<2	658	<2	<2	44.1	<1	99.7
MPRZB2	Muscle	887	8.3	<2	99.1	<2	<2	7.2	<1	77.2
MPRZB3	Muscle	950	8	<2	154	<3	<2	41	<2	136
MPRZB4	Muscle	973	5.3	<2	147	<3	<2	52.8	<1	77.6
MPRZB5	Muscle	980	3.9	<2	8.7	4	<2	67.4	<1	124
MPRZB6	Muscle	1400	24	<2	1230	<4	<3	174	<2	166
MPRZB7	Muscle	1100	14	<4	4	<10	<8	154	<5	346
MPRZB8	Muscle	914	3.4	<2	12	<2	<2	64.7	<1	113
MPRZB9	Muscle	1020	4.4	<2	<0.7	<2	<2	117	2	128
BLSED19 2	Sediments	11300	362	<5	10	22	2	259	25	63
BLSED20 2	Sediments	9900	373	<5	9	20	4	769	20	49
BLSED21 2	Sediments	7170	244	<5	7	16	3.3	523	16	34
BLSED22 2	Sediments	9780	295	6	9	21	4.8	537	23	47
BLSED23 2	Sediments	6850	253	<5	7	16	1	192	15	36
BLSED24 2	Sediments	10300	354	<5	10	23	4.2	389	27	63
DU2SED01 2	Sediments	8060	305	<5	8	10	1	323	16	33
DU2SED02 2	Sediments	6430	288	<5	<5	10	1	462	9.1	26
DU2SED03 2	Sediments	7880	296	<5	5	10	1	661	14	28
DU2SED04 2	Sediments	5580	242	<5	<5	9	1	622	7.8	14
DU2SED05 2	Sediments	7100	245	<5	6	10	<1	422	11	30
DU2SED06 2	Sediments	9170	298	<5	8	15	1	657	19	35
HLPSED13 2	Sediments	7160	391	<5	9	10	1	410	21	36
HLPSED14 2	Sediments	7230	305	<5	7	10	2	314	19	34
HLPSED15 2	Sediments	6710	351	<5	6	10	2	420	15	32
HLPSED16 2	Sediments	9970	502	<5	10	20	2	619	26	48
HLPSED17 2	Sediments	4730	245	<5	<5	10	1	248	10	18
HLPSED18 2	Sediments	10200	375	<5	10	20	2	461	26	50
OCSED07 2	Sediments	15300	875	<5	22	21	17	347	44	120
OCSED08 2	Sediments	14600	835	<5	24	22	<1	373	42	110

Appendix 3 continued.

dry weight, ppm		Mg	Mn	Mo	Ni	Pb	Se	Sr	V	Zn
OCSED09 2	Sediments	19400	1770	<5	28	30	<1	662	62	130
OCSED10 2	Sediments	17500	1430	<5	27	28	1	505	59	130
OCSED11 2	Sediments	11100	1010	<5	17	20	<1	263	43	100
OCSED12 2	Sediments	16000	1250	<5	25	23	<1	503	53	110
BWRBTC1	Whole Body	1050	9.4	<2	0.7	<0.2	2.4	150	1	79.4
BWRBTC2	Whole Body	1090	10	<2	4.5	<0.2	3	141	2.2	80.8
RZBDU2-1	Whole Body	1030	1.7	<2	<0.5	<0.2	3.1	152	0.5	189
RZBDU2-10	Whole Body	924	1.9	<2	1	<0.2	2.1	110	<0.5	141
RZBDU2-2	Whole Body	1040	3.2	<2	<0.5	<0.2	4	130	<0.5	135
RZBDU2-3	Whole Body	1050	2.7	<2	2.8	<0.2	2	159	<0.5	140
RZBDU2-4	Whole Body	972	2.1	<2	4	<0.2	2	118	<0.5	180
RZBDU2-5	Whole Body	941	1.6	<2	<0.5	<0.2	2.1	97.4	<0.5	128
RZBDU2-6	Whole Body	809	1	<2	<0.5	<0.2	1.9	99.5	<0.5	154
RZBDU2-7	Whole Body	979	1.6	<2	<0.5	<0.2	3.5	146	<0.5	174
RZBDU2-8	Whole Body	964	1.6	<2	1.6	<0.2	2.2	127	<0.5	143
RZBDU2-9	Whole Body	816	1	<2	<0.5	<0.2	1.8	101	<0.5	114

Appendix 3 continued.

wet weight, ppm		Al	As	B	Ba	Be	Cd	Cr	Cu	Fe	Hg	Mg
BL19W 2	Water	0.075	0.0045	0.44	0.143	<0.0005	0.0006	<0.002	<0.002	0.16	<0.001	85.1
BL20W 2	Water	0.11	0.0056	0.6	0.116	<0.0005	<0.0005	<0.002	<0.002	0.09	<0.001	129
BL21W 2	Water	0.05	0.0076	0.72	0.097	<0.0005	0.0006	<0.002	<0.002	<0.05	<0.001	154
BL22W 2	Water	0.066	0.0073	0.7	0.1	<0.0005	<0.0005	<0.002	<0.002	0.07	<0.001	149
BL23W 2	Water	0.062	0.0071	0.66	0.109	<0.0005	<0.0005	<0.002	0.0072	0.07	<0.001	145
BL24W 2	Water	0.085	0.0061	0.53	0.134	<0.0005	<0.0005	<0.002	0.002	0.09	<0.001	115
DU201W 2	Water	1	0.0067	0.51	0.105	<0.0005	<0.0005	<0.002	0.003	0.32	<0.001	66.4
DU202W 2	Water	0.23	0.0057	1.2	0.072	<0.0005	<0.0005	<0.002	0.002	0.19	0.002	180
DU203W 2	Water	0.05	0.0043	1.4	0.033	<0.0005	<0.0005	<0.002	0.003	0.09	<0.001	216
DU204W 2	Water	0.05	0.0084	1.5	0.051	<0.0005	<0.0005	<0.002	<0.002	0.07	<0.001	248
DU205W 2	Water	0.05	0.0039	1.4	0.058	<0.0005	0.0005	<0.002	<0.002	0.1	<0.001	236
DU206W 2	Water	0.35	0.0049	0.91	0.05	<0.0005	<0.0005	<0.002	0.004	0.25	0.001	166
HLP13W 2	Water	0.04	0.002	0.22	0.113	<0.0005	<0.0005	<0.002	0.002	<0.05	<0.001	39.6
HLP14W 2	Water	0.04	0.002	0.21	0.115	<0.0005	0.0007	<0.002	0.003	<0.05	<0.001	40
HLP15W 2	Water	0.02	0.002	0.21	0.113	<0.0005	0.0006	<0.002	0.002	<0.05	<0.001	40.4
HLP16W 2	Water	0.11	0.001	0.21	0.112	<0.0005	0.0008	<0.002	0.003	0.06	<0.001	40.5
HLP17W 2	Water	0.05	0.002	0.2	0.112	<0.0005	<0.0005	<0.002	<0.002	<0.05	<0.001	40.1
HLP18W 2	Water	0.078	0.002	0.22	0.111	<0.0005	<0.0005	<0.002	<0.002	<0.05	<0.001	40.6
OC07W 2	Water	0.24	0.012	2	0.049	<0.0005	<0.0005	<0.002	0.004	0.19	<0.001	18.2
OC08W 2	Water	0.14	0.011	1.9	0.048	<0.0005	<0.0005	<0.002	<0.002	0.08	<0.001	18.1
OC09W 2	Water	0.13	0.012	1.9	0.047	<0.0005	<0.0005	<0.002	0.002	0.07	<0.001	18.2
OC10W 2	Water	0.13	0.011	1.9	0.048	<0.0005	<0.0005	<0.002	0.002	0.07	<0.001	18.3
OC11W 2	Water	0.13	0.012	1.9	0.048	<0.0005	<0.0005	<0.002	0.002	0.07	<0.001	18.2
OC12W 2	Water	0.13	0.013	1.9	0.048	<0.0005	<0.0005	<0.002	0.002	0.08	<0.001	18.4

Appendix 3 continued.

wet weight, ppm		Mn	Mo	Ni	Pb	Se	Sr	V	Zn
BL19W 2	Water	0.11	<0.02	<0.005	<0.005	0.0009	2.5	0.002	<0.005
BL20W 2	Water	0.068	<0.02	<0.005	<0.005	0.0005	3.1	0.0034	<0.005
BL21W 2	Water	0.053	<0.02	<0.005	<0.005	0.0006	3.52	0.0036	<0.005
BL22W 2	Water	0.062	<0.02	<0.005	<0.005	0.0004	3.43	0.002	<0.005
BL23W 2	Water	0.059	<0.02	<0.005	<0.005	0.0005	3.41	0.002	<0.005
BL24W 2	Water	0.072	<0.02	<0.005	<0.005	0.00077	2.92	0.0031	<0.005
DU201W 2	Water	0.17	<0.02	<0.005	<0.005	0.0002	1.54	0.001	0.01
DU202W 2	Water	0.18	<0.02	<0.005	<0.005	0.0004	1.52	<0.001	0.019
DU203W 2	Water	0.0071	<0.02	<0.005	<0.005	0.0003	1.02	<0.001	0.01
DU204W 2	Water	0.099	<0.02	<0.005	<0.005	0.0003	3.2	0.002	<0.005
DU205W 2	Water	0.15	<0.02	<0.005	<0.005	0.0004	3.14	<0.001	0.02
DU206W 2	Water	0.048	<0.02	<0.005	<0.005	0.0004	1.51	<0.001	0.01
HLP13W 2	Water	0.038	<0.02	<0.005	<0.005	0.0004	1.29	0.0031	<0.005
HLP14W 2	Water	0.048	<0.02	<0.005	<0.005	<0.0002	1.3	0.003	<0.005
HLP15W 2	Water	0.041	<0.02	<0.005	<0.005	<0.0002	1.32	0.003	<0.005
HLP16W 2	Water	0.018	<0.02	<0.005	<0.005	0.0003	1.3	0.0034	0.01
HLP17W 2	Water	0.035	<0.02	<0.005	<0.005	<0.0002	1.3	0.003	<0.005
HLP18W 2	Water	0.02	<0.02	<0.005	<0.005	0.0003	1.3	0.0038	0.016
OC07W 2	Water	0.018	0.07	<0.005	<0.005	0.00087	0.501	0.017	0.01
OC08W 2	Water	0.016	0.069	<0.005	<0.005	0.0006	0.496	0.016	<0.005
OC09W 2	Water	0.015	0.069	<0.005	<0.005	0.00061	0.499	0.017	0.016
OC10W 2	Water	0.016	0.069	<0.005	<0.005	0.0005	0.502	0.017	0.005
OC11W 2	Water	0.016	0.07	<0.005	<0.005	0.00069	0.496	0.017	<0.005
OC12W 2	Water	0.017	0.07	<0.005	<0.005	0.0005	0.498	0.016	<0.005